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April 1997

US Army Corps of Engineers
Waterways Experiment Station

Environmental Impact Research Program

Capabilities of Laser Line Scan Technology for Aquatic Habitat Mapping and Fishery Resource Characterization

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Prepared for Headquarters, U.S. Army Corps of Engineers

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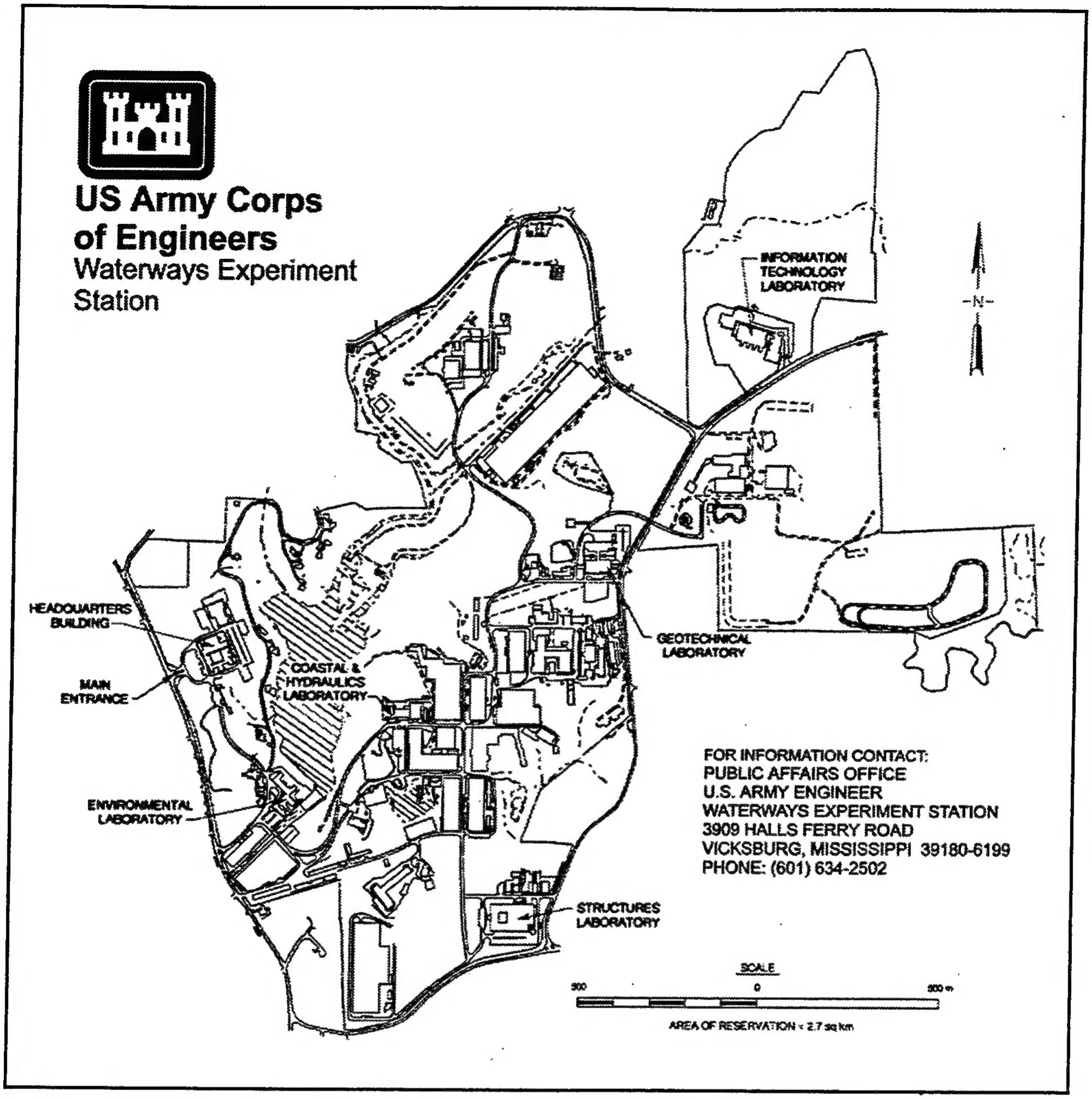

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US Army Corps of Engineers
Waterways Experiment Station

Environmental Impact Research Program

Capabilities of Laser Line Scan Technology for Aquatic Habitat Mapping and Fishery Resource Characterization (TR EL-97-7)

ISSUE: Environmental assessments in aquatic habitats are difficult for many reasons, including simple logistical constraints (e.g., vessel and navigation support), and the typically large spatial scales (e.g., hectares to square kilometers) that must be characterized. One of the most severe limitations that ecologists dealing with assessment of aquatic habitats must confront is available technologies. Gear conventionally employed for physical and biological characterizations remained essentially unchanged for decades. However, new technologies are emerging that offer enhanced capabilities in terms of parameters measured, spatial coverages, data analysis response times, and, ultimately, improved cost-effectiveness.

RESEARCH OBJECTIVE: Previous work identified a number of candidate technologies that appeared to provide greatly improved capabilities for aquatic habitat assessments. One of the most promising new technologies was found to be the laser line scan system (LLSS). This report describes in detail the capabilities of LLSS technology, with an emphasis on potential applications to Corps of Engineers projects.

SUMMARY: This report provides an in-depth description of the LLSS, an optical-sensor-based technology that can produce high-resolution images of biological resources and aquatic habitat features. Topics covered include basic design and sensor specifications, operational protocols and constraints, data products, and comparisons with other optical and acoustic survey systems. Example applications of this technology for mapping deposits of dredged material, detection of construction debris and industrial wastes, and surveys of demersal fish and shellfish populations are given. Although in its prototype configuration the LLSS is moderately expensive to employ, anticipated design advancements should improve overall cost-effectiveness. This system should prove to be a valuable option for future aquatic habitat assessment needs within the Corps.

AVAILABILITY: The report is available on Interlibrary Loan Service from the U.S. Army Engineer Waterways Experiment Station (WES) Library, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199; telephone (601) 634-2355. To purchase a copy, call the National Technical Information Service (NTIS) at (703) 487-4650. For help in identifying a title for sale, call (703) 487-4780. NTIS numbers may also be requested from the WES librarians.

About the Authors: This report was written by Drs. Donald Rhoads and Drew Carey, Senior Scientists at Science Applications International Corporation, Mr. Edward Saade, Division Manager at Science Applications International Corporation, and Dr. Barbara Hecker, Hecker Environmental Consulting. **Points of contact** are Dr. Carey (401) 848-4770 at SAIC, and Dr. Douglas Clarke (601) 634-3770 at the U.S. Army Engineer Waterways Experiment Station.

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Preface

The work reported herein was conducted by the U.S. Army Engineer Waterways Experiment Station (WES) for Headquarters, U.S. Army Corps of Engineers (HQUSACE). Funding was provided by HQUSACE through the Environmental Impact Research Program (EIRP), Work Unit 32883, entitled "New Technologies for Evaluation of Aquatic Habitats." Program Manager for the EIRP was Dr. Russell F. Theriot.

This report was prepared by Drs. Donald C. Rhoads and Drew Carey, and Mr. Edward Saade of Science Applications International Corporation, and Dr. Barbara Hecker of Hecker Environmental Consulting. Technical oversight of the project was provided by Dr. Douglas Clarke, Ecological Research Division (ERD), Environmental Laboratory (EL), WES. Additional technical review of the report was provided by Dr. Gary Ray, ERD.

The work was performed under the general supervision of Dr. Douglas Clarke, Acting Chief, Coastal Ecology Branch, ERD. The Chief of ERD was Dr. Conrad J. Kirby, and Director of EL was Dr. John Harrison.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
gallons (U.S. liquid)	3.785412	cubic decimeters
inches	2.54	centimeters
knots (international)	0.5144444	meters per second
miles (U.S. nautical)	1.852	kilometers
pounds	0.4535924	kilograms
tons (2,000 pounds, mass)	907.1847	kilograms

1 Introduction

This paper is an elaboration of an earlier review of sensors that are used for efficient assessment of submerged coastal habitats and biological resources (Rhoads, Muramoto, and Ward 1994). This document outlines in greater detail the operational principles of the laser line scan system (LLSS), method of deployment, data acquisition, and post-cruise data analysis protocols. While the LLSS system has a wide range of potential applications, the emphasis here is on mapping and monitoring seafloor (or lake bottom) features that are of particular interest to the U.S. Army Corps of Engineers such as mapping of sediment types, biological resources, dredged material footprints, and underwater structures such as submerged parts of dikes, dams, levees, or discarded waste containers.

Historically, rapid mapping of oblique "panoramic" views of the seafloor was exclusively done by towed acoustic side scan. Object resolution of a 50-kHz acoustic side scan is on the order of ≥100 cm. The LLSS is an optical system that has the potential for object resolution of a few millimeters to centimeters. A conventional ORE 50-kHz side-scan sonar has been integrated into the LLSS towfish specifically for nearshore seafloor reconnaissance. This dual laser/acoustic sensor is called the Underwater Laser Imaging Survey/Inspection System or ULISYS (Figure 1). This sensor pair has already been successfully used in disposal site surveys (e.g., Hellemn, Fredette, and Carey 1994). This towed 2-W Argon laser operating in the blue-green spectrum (output mainly at 488 and 514 nm) yields superior, picture quality images and has been used to map gradients in dredged material type, distribution of hard and soft bottom, distribution of disposed waste containers, and biological resources such as demersal fish, lobsters, and other megafauna and macrofauna. The sensor can be towed at speeds up to 6 knots[1] in water depths to 690 m at an altitude of 2.5 to 39 m above the bottom depending on ambient turbidity. Light backscatter in turbid environments is minimized by the small single point of coherent light moving across the bottom. The LLSS extends the imaging range by a factor of 2 to 3 over conventional video imaging. The bottom image is built up from a rapidly acquired series of spots on the seafloor, each sequentially illuminated by a laser beam about as wide as the diameter of a pencil. The user can select the desired resolution from 512, 1,024, or 2,048 pixels across a fixed 70-deg field of view. The video signal has a

[1] A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page ix.

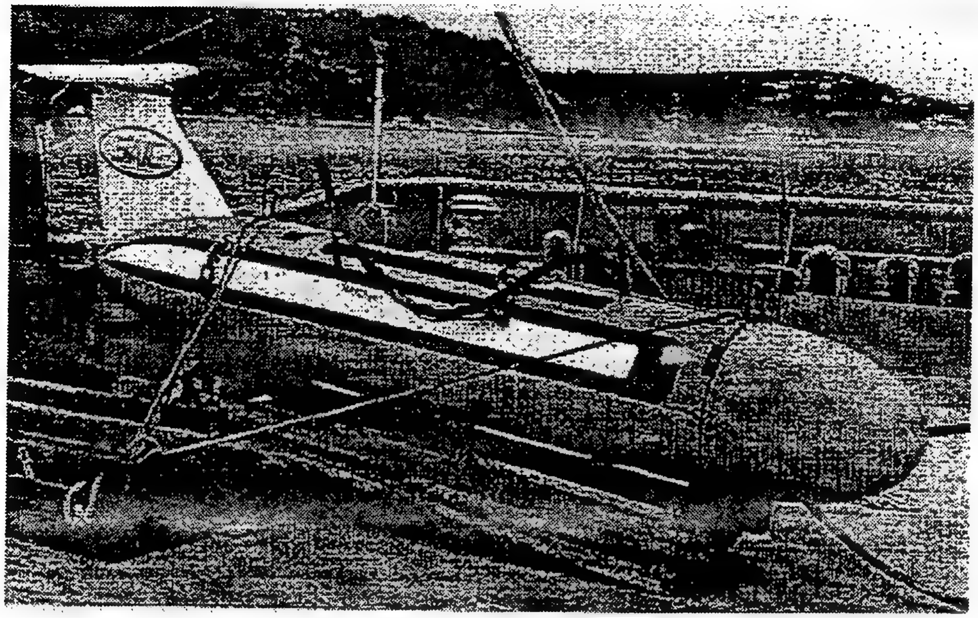

Figure 1. The ULISYS vehicle used in disposal site surveys in New England waters. This prototype is 4 m long and weighs 500 kg. This early prototype has a spectral output mainly in the 488- and 514-nm range (from Hellemn, Fredette, and Carey (1994))

dynamic range of 72 dB (12 bits). Data are transmitted topside via fiber-optic cable and the data can be postprocessed from Super VHS analog videotape as well as 8-bit continuous and 12-bit "snapshot" digital data. Onboard equipment also includes a control console for all system functions and visual displays of sensor status data and video data. The major benefits of the optical scanning system relative to traditional acoustic imaging is the higher optical resolution and the possibility of doing spectral analysis of frame grabs in the near future (see Chapter 7).

Because of the high optical resolution of the LLSS, information about the distribution and abundance of biological resources (often identifiable to genus or species) can be made. These data can be acquired by a frame-by-frame analysis, recorded in a database, and graphically displayed as transect scatter plots, stick diagrams, histograms, or frame-averaged transect trends. Correlation and association techniques as well as multivariate pattern recognition (community analysis) may also be utilized to investigate the relationship between the distribution of fisheries resources and physical parameters of the benthic environment such as sediment type, dredged material distributions, and seafloor topography. A few examples of these techniques are given in Chapter 5.

2 System Description

Overview

The towed LLSS is a 2-W blue-green solid state laser optical device designed for acquiring high resolution large area surveys of the seafloor or lake bottom. The LLSS system is capable of detecting millimeter to centimeter size objects at ranges from two to four times the range of conventional underwater camera and light systems. Operation of the LLSS is based on the latest advances in laser scanning technology. Laser scanning, in essence, can be described as the building up of an image from a rapidly acquired series of spots on the bottom, each sequentially illuminated by a pencil-sized diameter laser beam. This technique of underwater imaging minimizes the effects of backscattered and forward-scattered light, permitting increased range and high resolution data collection over conventional film or video cameras.

The sensor can be towed at speeds up to 6 knots in water depths to 690 m at an altitude of 2.5 to 39 m above the bottom depending on ambient turbidity. Light backscatter in turbid environments is minimized by the small single point of coherent light moving across the bottom. An LLSS bottom image is built up from a rapidly acquired series of spots on the seafloor, each sequentially illuminated by a laser beam about as wide as the diameter of a pencil. The user can select the desired resolution from 512, 1,024, or 2,048 pixels across a fixed 70-deg field of view. The video signal has a dynamic range of 72 dB (12 bits). Data are transmitted topside via fiber-optic cable and the data can be postprocessed from Super VHS analog videotape as well as 8-bit continuous and 12-bit "snapshot" digital data. The LLSS is compactly packaged in a rugged pressure housing as part of the towed vehicle. As described above, the towfish may also include a conventional acoustic side scan. This rapid screening exercise is sometimes needed to make a high altitude "first pass" with the acoustic sensor in order to evaluate the risk of flying the LLSS nearer the bottom. This is particularly important in areas that are uncharted or in areas where there are wrecks, debris, snags, or high topographic relief. Data from the LLSS are transmitted via a fiber-optic or copper conducting cable to the monitoring and recording station on the survey vessel. Onboard equipment includes a control console for all system functions and visual displays of sensor status data and video data. Major benefits of the optical scanning system relative to traditional acoustic imaging are the higher optical resolution and the possibility of doing spectral analysis in the near future (see

description of Dual-Mode Fluorescence Imaging (DFI) technology in Chapter 7). A single operator can adjust LLSS parameters (e.g., fly height), monitor output in real time and control data recording in video or digital format on tape. Survey operations are conducted in a manner similar to side-scan sonar surveys.

Currently, the tow vehicle is configured to operate as a "heavy fish" to depths in excess of 2,000 ft. By the spring of 1996, Science Applications International Corporation (SAIC) will deploy a neutrally buoyant vehicle which can attain depths in excess of 10,000 ft and maneuver up, down, left, and right. Given this extreme depth capability and flight capability, this is one of the only imaging technologies that can be used for deep-water disposal site surveying. Information acquired by this system permits post survey analysis in a convenient SVHS video format as well as 8-bit continuous and 12-bit "snapshot" digital format. In addition, mosaics assembled from overlapping imaged transects or individual frames can be generated for display and presentation purposes.

The latest version of the LLSS, which is called the SM2000, is manufactured by Westinghouse, and owned by SAIC. This is a solid-state, blue-green laser with most energy produced in the 528-nm range. The emitted light strikes a rotating prism mirror which projects the laser beam onto the seafloor. The beam is directed across the bottom in a direction perpendicular to the flight path of the towfish. A photo multiplier tube processes the reflected return of this narrow beam swath into a single optical scan. By maintaining the prism rotation (laser sweep rate) proportional to the towfish speed, the LLSS system builds up an optical image of the seafloor by assembling each line scan with adjacent scans (Figure 2). Adjustments to scan angle and depth of field can optimize the image for specific imaging requirements. The maximum lateral scan angle is 70 deg which provides a swath width equal to 1.4 times the towfish fly height. Minimum scan width is 15 deg. Each scan is digitized as 1,280 pixels. Decreasing the scan angle increases the density of pixels per unit of swath width and therefore increases image resolution. The depth of field is controlled by a mechanical shutter that determines what vertical portion of the reflected signal reaches the photo-multiplier for processing resulting in a form of range-gating.

Optical Sensor

The underwater optical sensor consists of the imbedded sensor control electronics subassembly, the laser subassembly, the scanner subassembly, and the detector assembly. These four subassemblies are integrated into a single physical assembly and installed inside a watertight cylindrical pressure vessel (Figure 2).

The SM2000 scanner subassembly is composed of two rotating, four-faceted mirror assemblies which are rigidly attached to a common rotating shaft. The illumination laser is oriented such that its output beam is incident to one of the mirror assemblies. The laser beam is reflected toward the bottom, illuminating the surface. The receiver views the larger of the

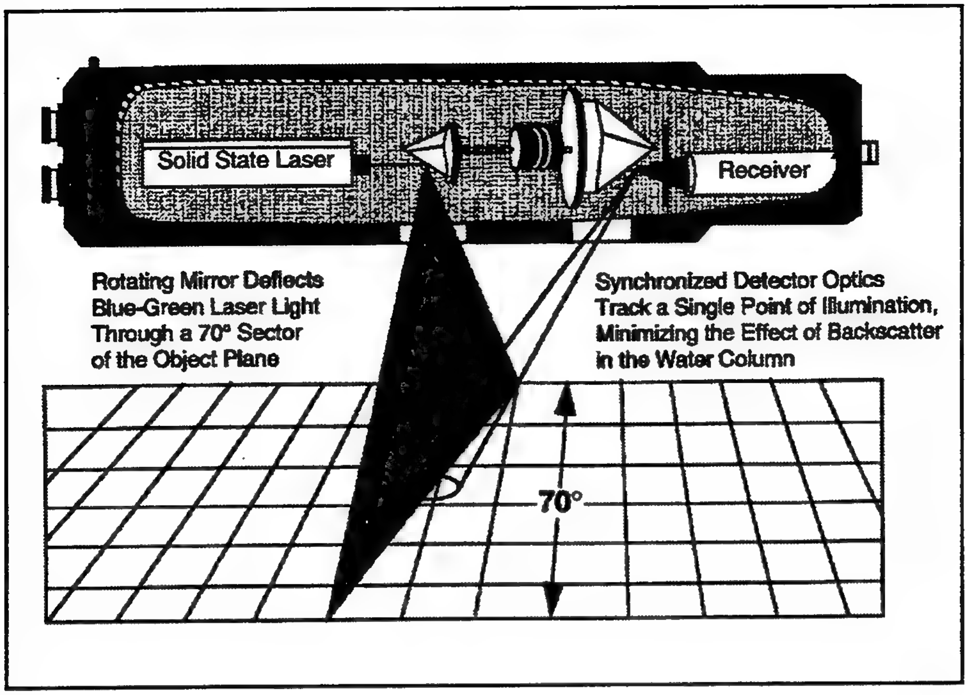

Figure 2. Operational concept of the scanning laser spot which is assembled into a line-by-line image on the vessel's monitor as the survey is under way

mirror assemblies and synchronously scans (i.e., views) the laser spot on the bottom. As the laser beam travels toward the bottom, a fraction of the beam energy is scattered and adsorbed by the water. Adsorption and scattering introduce noise in the image and reduce contrast. These processes have historically made it difficult to produce high-quality images of submerged objects at acceptable operating ranges with conventional video or film cameras. While the LLSS is not totally immune to adsorption and scattering problems, these problems are minimized by the intense narrow laser beam.

The unscattered and unabsorbed laser light that does reach the bottom illuminates a small, localized area that is called the primary scan spot. This is the area of greatest interest because it is from this area that the optical return signal is generated. As the mirrors rotate, the scan spot traces a continuous line across the bottom, instantaneously illuminating a very small strip of the bottom. By synchronizing the scan rate with the relative velocity between the towed sensor and bottom, it is possible to control the spacing between adjacent scan lines and thereby ensure that a rectangular sample pattern and image aspect ratio are maintained.

The bottom reflects a portion of the incident energy back toward the sensor. If the scan spot is incident on a bright (reflective) portion of the target, a relatively large fraction of the incident energy is reflected back to the receiver. Conversely, if the bottom adsorbs 528 nm light, only a small fraction of light will be reflected back to the receiver. The reflected energy is scattered and adsorbed on its return path to the sensor and the remaining energy enters the receiver through the receiver aperture and cylindrical input window. If the power in the laser beam is held constant,

and if certain geometric factors are ignored, then it can be assumed that the amount of energy reflected by an object on, or near, the bottom is proportional to the “local reflectance” of the target. In this case, local reflectance represents the reflectance of the target averaged over the area illuminated by the primary scan spot.

By sampling the output of the photo-multiplier tube (PMT) at times that are synchronized with the mirror rotation, it is possible to build up a two-dimensional reflectance map of the bottom. This is accomplished by digitizing the sampled PMT signal and storing the resulting digital data in a video random access memory module. The stored data can then be read and displayed by a CRT controller. If the whole process of data acquisition, storage, and display is properly integrated and synchronized, then there is a direct relationship between each physical location of a target-of-interest on the CRT screen and the relative location of that target on the bottom. As the sensor passes over a stationary object on the bottom, the display can be controlled in such a way that data from each new acquired scan line are always displayed at the top of the CRT screen. This requires that all previous lines move down the screen to make room for new lines. This process results in a “waterfall” display that gives the operator a very realistic view of the passing seafloor and objects of interest.

Communications Link

The communication/power cable transmits video data and status from the optical sensor to the control console and transmits command data from the control console to the optical sensor. The cable contains fiber-optic channels and metallic electrical conducting wires as well as strength members for towing.

Control Console

The control console provides the operator with control over all system functions including electrical power, data management, data display, data recording, scan rate, sampling rate, adjustable aperture positions, beam position, PMT gain, laser output power, automatic gain control (AGC) mode, sensor altitude and speed inputs, channel equalization and shading correction (required because the signal return from the target areas at the edge of the scanning field have larger attenuation and path loss). Most of these functions are normally controlled automatically but the operator is given the ability to override these automatic features and control any desired function manually. The control console also provides the operator with displays of sensor status and video data. Status data are displayed on the virtual control panel and video data are displayed on a separate high-resolution video monitor. The operator can record individual images in digital form on the console computer’s hard disk or record live video in analog form on a standard video cassette recorder using the NTSC RS-170 video output.

3 Mobilization, Deployment, and Field Survey Protocols

Mobilization and Deployment

Mobilization of the LLSS requires the following steps: system check-out, transportation of system to vessel, installation of system and support equipment on vessel. Depending on the vessel size and capabilities, one to two days should be allowed for system checkout and installation.

System checkout

Pre-cruise mobilization requires cleaning of the optical path inside the pressure vessel including the following components: rotating mirror assemblies, lenses, and optical ports. Following cleaning and checking internal components, the pressure vessel must be charged with anhydrous nitrogen gas and sealed. After installation on the vessel, the operating console, cable, slip-ring and towfish must be connected and "wrung-out" to ensure fiber-optic and electrical continuity. A detailed summary of system checks is beyond the scope of this review. However, experience has shown that two technicians require one day prior to installation and one-half day after installation to properly check out the system.

Transportation

The entire system and any supporting equipment (winch, slip-ring, sheave) must be packed and crated for shipment and/or loaded onto a boat or car trailer for transport to the survey vessel. The current towfish is 14 ft long and weighs 2,000 lb in air. Any shipping or loading limitations must be coordinated with the survey vessel and mobilization sites.

Installation and vessel support requirements

Installation on a vessel previously used for the system can be performed in one day with three technicians. Deployment requires the following

attributes on the vessel (attributes *a* and *b* can be installed during mobilization):

a. Dedicated electro-optical conducting slip-ring winch (note large reel trawl winches can be modified to incorporate slip-rings).

b. Large diameter (>36-in. diam) sheave.

c. Large deck space (optimal: 20 ft by 30 ft aft space, provisions to mount the winch near centerline of "A" frame on a structurally secure section of deck).

d. Adjustable stern "A" frame or crane with minimum capacity of 5 tons, 15 ft clearance under frame, 12 ft wide at chest level, provisions for positioning tow point 8 ft forward or sternward of transom.

e. 50-kW 3-phase power for winch and laser.

f. Vessel of 80 to 100 ft able to maintain course at 2 knots.

Preparation of an LLSS Survey Plan

Presurvey planning determines the successful outcome of an LLSS survey. The following eight points should be considered to establish a survey protocol:

a. Water column conditions.

b. Ambient light conditions.

c. Preliminary bathymetric survey.

d. Preliminary side-scan sonar survey.

e. Survey scale.

f. Navigation.

g. Survey objectives.

h. Survey priorities.

SAIC's experience in the NY Bight during the spring of 1993 demonstrates how important it is to know what the optical properties of the water column are at the site and how they change on both a seasonal and daily basis (Inglin 1994a). Flood conditions in the Hudson River prior to the survey created high turbidity in the area and reduced the usefulness of the LLSS. Before deploying the LLSS, a 10-cm light path transmissometer cast was made to evaluate whether the LLSS would be capable of providing images. Water column conditions were very limiting at the Ambrose Channel borrow pits and the New York Mud Dump site, where transmissivity was measured to be 0.1 to 5 percent near the bottom. This low transmissivity reduced the operating altitude of the towfish to a point where it

was unsafe to operate. In other areas (Hudson River Canyon walls, outer New York Bight) transmissivity as low as 10 percent allowed the towfish to be operated at an altitude of 10 ft but did not provide optimal working conditions in these offshore areas. If a survey site, or part of a site, is located in shallow water where there is significant penetration of sunlight to the bottom, scattered ambient light may compromise image quality of the LLSS. If this is the case, an LLSS survey will have to be conducted during the night.

A detailed bathymetric survey is invaluable in planning a survey with the LLSS. If a prior survey is not available, it is recommended that the area be surveyed before towing the LLSS. The towfish must be towed close enough to the bottom to allow the PMT to receive a signal. The altitude of the towfish is dependent on water clarity and must be less than about 5 optical attenuation lengths. In New England and New York waters, typical towfish altitudes are between 25 ft at Cohasset Ledge, MA (rock debris with little suspended material above the bottom) to about 8 ft in the muddy basin of central Long Island Sound and within the Hudson Canyon (Inglin 1994). At Cohasset, the depths varied dramatically with steep rock ledges protruding 2 to 10 ft above the bottom. These conditions required bathymetric transects prior to each LLSS tow and operation at the full working altitude (25 ft). Careful planning is required to avoid having the towfish hit bottom in areas where there is rapidly changing bathymetry.

Another aid to navigating the towfish is a side-scan sonar survey of the area of interest. This supplements the bathymetric survey by clarifying areas to avoid while towing the LLSS towfish. A second reason for performing a preliminary side-scan sonar survey is to pinpoint areas of interest and reduce the area where LLSS coverage is required. The LLSS is a high-resolution imaging tool with coverage rates that are relatively fast compared to other technology capable of similar resolutions. However, typical LLSS coverage rates (18,000-59,000 m^2/hr) are an order of magnitude less than the coverage rates of a side-scan sonar at a swath range of 100 m per side. For this reason a preliminary side-scan sonar survey can improve the efficiency of an LLSS survey by narrowing the LLSS search pattern to only those areas of greatest interest. The LLSS system provides a scale between a side-scan sonar survey and a towed video or film camera sled or remotely operated vehicle (ROV) survey. Side-scan sonar and bathymetry provide the first level of detail which serves as a foundation in the planning of more detailed phases of a study.

Perhaps the most critical factor influencing the successful outcome of an LLSS survey is navigation. Navigation of both the vessel and the towfish must be of the highest accuracy possible, especially if the target is of small scale such as a dredged material footprint. Targets that the LLSS is capable of resolving are relatively small. Determining the geodetic locations of the targets is usually a primary goal of a survey; therefore, the navigation system must be able to resolve the ship and towfish location within an error comparable to the size of the objects. It is also important to use navigation systems with the same degree of accuracy (if not the same system) for all phases of a particular study. Presurvey planning must accommodate these considerations. Survey objectives determine the navigation accuracy required for a particular investigation. In the case of a Boston Light Ship survey, for example, the intention was to locate and

identify old discarded 55-gal drums that, at one time, contained industrial waste. The navigation system used for this type of survey must be capable of determining position within 1-5 m to confidently map targets or find them again during future surveys (Inglin 1994a).

A final consideration in designing an LLSS survey is to have a clear idea of survey priorities. The quantity of information collected by the LLSS can be overwhelming in terms of analysis time (typically 15 to 30 min per minute of survey) if the goals are not clearly delineated and understood by all involved. This is true of most oceanographic surveys, but it is particularly important with the LLSS. Multiple objectives are possible, but definition of the primary goal maximizes the efficiency of field operations.

4 Examples Relevant to Typical COE Projects

Mapping of Dredged Material

The LLSS provides a new tool for investigating the distribution of dredged material at designated disposal sites. We do not suggest that the LLSS totally replace current methods of mapping dredged material distribution (e.g., precision bathymetric surveying, sediment-profile imaging, side-scan sonar surveys, and/or benthic grab/core sampling). Rather, when used in a tiered approach, LLSS is a useful second tier sensor following an acoustic side-scan/bathymetric (tier one) reconnaissance investigation. An LLSS survey may, in turn, be followed by smaller scale and higher resolution (tier 3) sensors such as sediment profile imaging. Finally, if the tiered management protocol requires actual sediment sampling for chemistry or biology, the fourth tier may involve grab or core sampling.

Normally, a tier one predisposal side-scan and bathymetric survey provides a baseline to which later bathymetric surveys can be compared. Completing an LLSS survey of the area at the same time provides a visual record of the baseline conditions at the site and allows comparison with subsequent surveys to detect changes in surface sediments. This protocol is particularly useful at sites where ambient sediment conditions are variable across the site or where it is predicted that dredged material will be difficult to distinguish with acoustic methods alone.

Often one of the goals of a dredged material site survey is to map recently deposited dredged materials and to distinguish these from older dredged material deposits. The LLSS was successful in identifying dredged material of various types and different ages at the Massachusetts Bay Disposal Site (MBDS) where recently disposed cohesive clay blocks (Figure 3) and rocky material (Figure 4) were diagnostic of the footprint (Inglin 1994b). SAIC's experience indicates that the LLSS is advantageous at particular points in a traditional survey. Used in the first phase of a dredged material distribution mapping survey, along with the usual predisposal precision bathymetric survey, this technology can aid in the interpretation of data. Additional bathymetric surveys traditionally are completed both during and after disposal. In a second LLSS mapping exercise, conducted in conjunction with the postdisposal bathymetric survey, one

Figure 3. LLSS frame grab of recently disposed cohesive clay blocks at the Massachusetts Bay Disposal Site (MBDS). From Inglin (1994b)

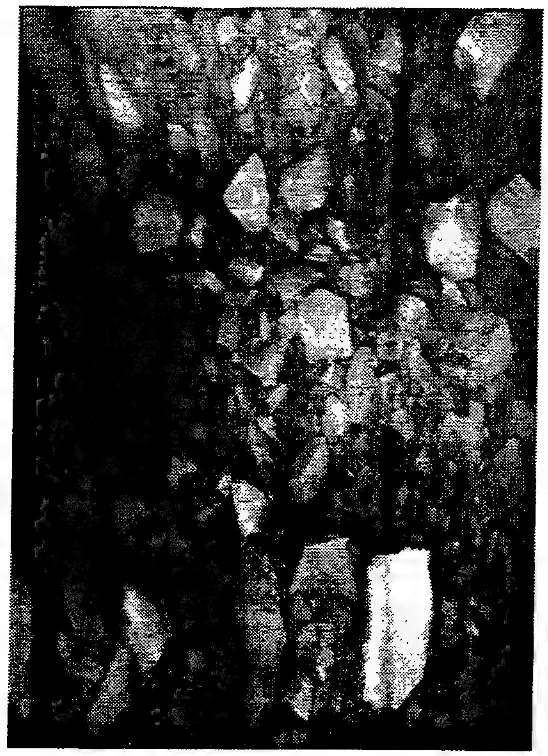

Figure 4. LLSS frame grab of disposal rock debris from the MBDS. From Inglin (1994b)

survey, one may compare sediment texture and grain size with the baseline LLSS survey to map the flanks of a mound.

Typically, sediment-profile imaging is used as a third tier sensor to define the lateral extent of the dredged material disposal mound by measuring dredged material thickness at increasing distances from the mound center. This is necessary due to the resolution limitations of acoustic bathymetric surveys. Using the LLSS enhances this method of defining the flanks of the mound. It provides a plan-view visual record of the gross texture and boundary roughness at the sediment surface along transects crossing the mound.

Use of the LLSS does have a drawback. The LLSS is significantly costlier than the other dredged material mapping techniques mentioned above (see Chapter 6). While obtaining continuous, photographic-quality images of the disposal site is desirable, the cost of using the LLSS must be compared and weighed relative to other methods. Therefore, while the LLSS is not recommended as a routine monitoring tool, its effective use in special projects cannot be dismissed.

The striking images of the seafloor can be very effective in public relations presentations. Used in a slide presentation to explain the environmental effects of dredged material disposal to a general audience, for example, the images can spatially orient the viewers relative to the ambient bottom, disposal mound flanks, and mound apex. An image of recently disposed rocky material, shell/gravel armoring, a sediment plume, or aggregation of fish or lobsters makes meaningful what was before a technical term, line drawing, graph, or table. This application is particularly effective in demonstrating visually that coarse-grained capping material has covered fine-grained contaminated material and that disposal sites are not biological deserts but productive topographic features.

The LLSS can also aid in assessing dredged material loss. Bathymetric survey analysis sometimes identifies areas where material appears to have been lost from a disposal mound. When contaminated sediments are disposed, determining whether the material has actually been transported from the mound or that the decrease in mound height is due to consolidation becomes a management concern. The high-resolution LLSS images provide evidence that indicates whether the bottom has been scoured by currents or whether compaction might explain volume reduction. For example, the LLSS images might reveal the presence of small bedforms or lag deposits of coarse material on the sediment surface, indicating scour by bottom currents. If, on the other hand, images record a smooth surface, possibly showing biological recolonization, this information strongly supports the idea that mound height reduction is related to sediment compaction rather than surface erosion.

Used appropriately, images recorded by the LLSS are another data source to monitor changes at a dredged material disposal site. Especially at areas containing contaminated sediments, judicious use of the LLSS can focus an investigation on the particular areas of concern and establish a visual datum for further comparison. The high-resolution images recorded by this survey tool can also be used in reporting to an increasingly concerned public the dynamics of open water disposal of dredged material.

Construction and Industrial Waste

The LLSS is particularly well-suited for searching, identifying, and assessing the distribution of structures that have a good optical signature but poor acoustic return. It is widely known that construction and industrial debris have been dumped in the nearshore region. There are numerous reports, both verified and unverified, of such debris in areas which are not known to be either present or historic disposal sites. Even in known

historic disposal sites such as the NY Mud Dump and the Cellar Dirt site, neither the distribution nor the type of debris disposed is well-documented. Records of historic disposal are vague if they exist at all.

An LLSS survey conducted at the MBDS illustrates the capability of the LLSS to map disposed structures. Presently, the MBDS is being used for dredged material disposal. MBDS intersects the historic Industrial Waste Site (IWS) where an unknown number of hazardous and low-level radioactive waste containers were disposed between 1953 and 1959. Disposal of hazardous waste containers continued at the IWS until 1976. In addition, large amounts of industrial and construction debris have been reported in this area including pipes, concrete rubble, and telephone poles. A previous survey using side-scan sonar and an ROV was completed in the area by SAIC for the Environmental Protection Agency (Wiley et al. 1992). This survey provided side-scan sonar records that allowed the LLSS survey to be concentrated in a specific area where these records indicated a field of targets. The subsequent LLSS survey was able to identify and characterize visually (as corroded, smooth, broken, buried, or upright) 16 barrels (Figure 5) (Wiley et al. 1992). This survey was also able to identify a rock pile from disposal of material blasted from the Third Harbor Tunnel project (Figure 4), and numerous concentrations of rubble, pipes, and wooden beams. It was particularly striking to record numerous piles of obstructions (pipes, construction materials) that were not distinctive on side-scan records but were located in an area known to contain debris (Figure 6). By observing and noting the location of these piles, the disposal site can be managed more effectively.

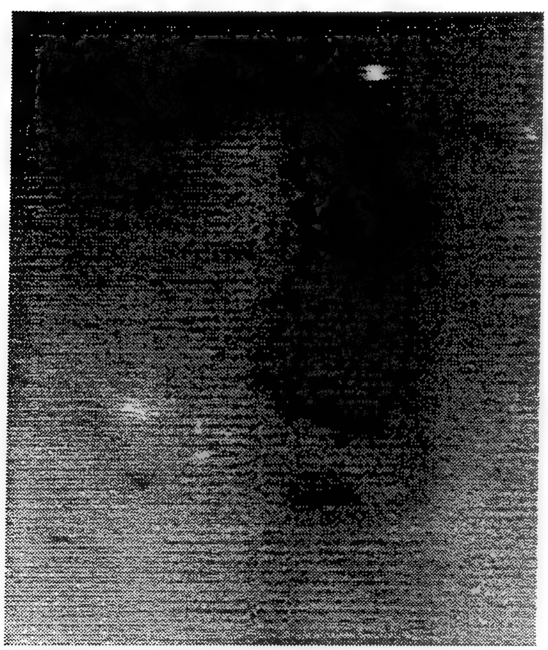

Figure 5. LLSS frame grab showing corroded waste barrel from the MBDS. From Inglin (1994b)

Comparing the coverage rate of the two survey techniques illustrates one characteristic unique to the LLSS: its speed. The ROV surveyed portions of the IWS chosen from side-scan sonar records. Operators in this 1992 survey covered approximately 23,000 m^2 (20 m radius at 18 anchorages) in 140 hr. The ROV allowed direct viewing of 64 metal containers

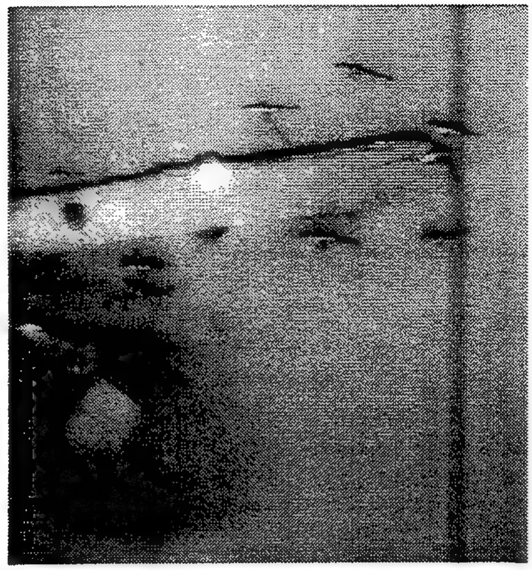

Figure 6. LLSS frame grab showing wooden beam, demersal fish, and corroded barrel from the MBDS. From Inglin (1994b)

(about 1 barrel for every 2 hr of survey time) with interactive navigation around the anchorages. This yielded a coverage rate of 164 m^2/hr. The LLSS survey, on the other hand, allowed a coverage rate of 28,000 m^2/hr. During a calibration run over the IWS, the LLSS operators identified 14 barrels in 1.5 hr, an observation rate of about 9 barrels/hr. Clearly, the rapid survey rate is a major strength of the LLSS.

In the MBDS survey, a side-scan survey of the disposal area was made before using the LLSS. Interpretation of the side-scan sonar data allowed operators to predict a likely location for targets. For example, when the intended target is metal drums, the side-scan sonar often detects their unique "double ring" signature. Once suspected natural and manmade targets are mapped, the LLSS survey can focus on these locations, and on areas where the side-scan sonar is unable to resolve objects. It proved helpful for the field survey team to preview sample frame grabs of targets during the survey. Having such a reference library increases the likelihood of target recognition and improves real-time recording of target locations. The resulting map is both more complete and more quickly produced. In segments of the LLSS survey where densities of objects are too high to count in real time, these segments are noted and analyzed in greater detail following the survey. Because the navigation used for the preliminary side-scan sonar survey recorded the vessel position only, rather than tracking the side-scan sonar towfish, the survey team was unable to reliably correlate features in the LLSS record to targets identified in the side-scan sonar survey. This was a definite shortcoming, because the primary objective of the survey was to locate targets that might be low-level radioactive waste containers. Clearly, accurate navigation of the towfish is key to mapping the location of targets.

Demersal Fish

The effect of disposal on demersal fish populations is commonly a management issue. Traditional approaches using trawls or fixed trammel nets

for assessing demersal fish populations on disposal sites relative to the ambient bottom have not proven efficient. The LLSS is capable of producing sufficiently high-resolution images of demersal fish that species may be identified and counted (see Chapter 5). The LLSS records the relationship between fish and habitat without altering the physical environment by removing the fish with a trawl net. Data may be recorded using LLSS frame grabs and a tally system. Future image analysis software developments, such as automated pattern recognition software, would allow development of a library of images to which new images could be compared.

The LLSS is capable of collecting information, relating to fish in the water column, that other bottom survey tools currently are unable to access. The ability allows one to record fish trails (areas where the sediment had been disturbed as a fish swims close to the bottom; Figure 7) and shadows of fish in the water column. The LLSS provides information about the height of organisms in the water column as well. The shadows of fish and the actual image of the fish (sometimes only an unrecognizable black shape) can be used to provide the height of that fish off the bottom (Figure 8).

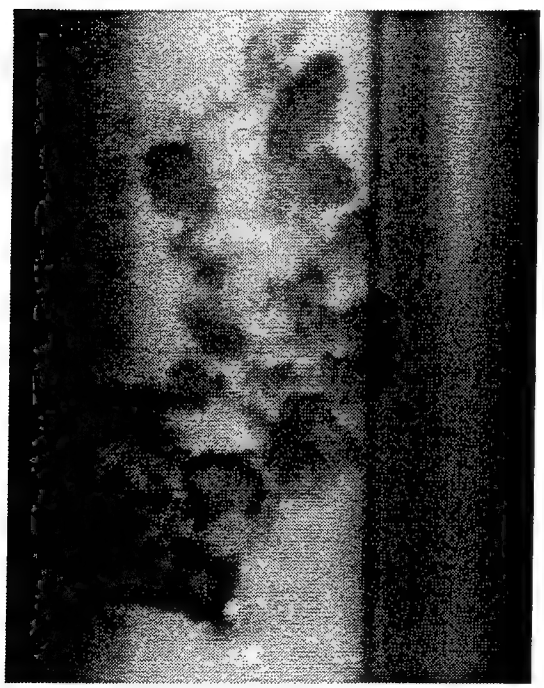

Figure 7. LLSS frame grab of fish trail at the MBDS. From Inglin (1994b)

Some sampling bias is inherent in the LLSS records as images only show the presence of those fish that do not move out of the field of view as the towfish approaches. Even so, the results obtained are probably comparable to the "collection" efficiency of using a towed net. Under high visibility water conditions, the LLSS can be towed high enough above the bottom to eliminate fish avoidance of the towfish pressure wave. Future evaluation of the efficiency of the LLSS relative to trawling should include an experimental comparison of the two methodologies.

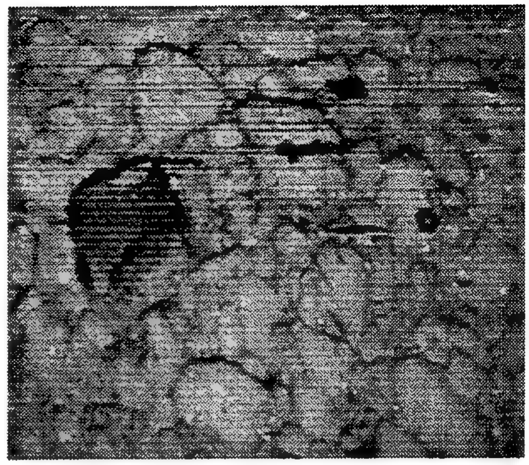

Figure 8. LLSS frame grab showing fish and shadow (from Inglin (1994b)

Benthic Resource Assessments

A demersal fish distribution survey was one component of a more comprehensive biological and physical investigation of the benthos conducted during the SAIC/New England Division LLSS capabilities study (Inglin 1994b). Benthic resource assessments commonly attempt to answer a question central to dredged material management: What effect will dredged material disposal have on the benthic habitat? Such an assessment focuses on three aspects including habitat classification, geological resource identification and mapping, and species distributions. All require an accurate picture both of the distribution of the habitat (i.e., scale or patch size) and of the distribution and abundance of organisms within that habitat. Many of the advantages demonstrated by the LLSS in fish distribution studies would be of particular value in a complete benthic resource assessment. In this instance, our inquiry centered on the importance of the LLSS in investigating benthic resources.

The Benthic Resources Assessment Technique (Lunz and Kendall 1982; Clarke and Lunz 1985) is a method used to investigate the value of the benthic environment to commercial species and hence its importance to man. This technique "estimates the amount of the benthos at a given site that is both vulnerable and available to target fish species" (Clarke and Lunz 1985). The morphological, temporal, and spatial distributions of the target fish species are determined with traditional trawling techniques, and the benthic community is characterized using box cores. The spatial distributions of the benthic organisms are then extrapolated over the survey area.

In order to spatially extrapolate biological distributions confidently, an accurate map of the bottom type must be available. Techniques that have been used traditionally to study and classify the benthic environment include sediment-profile cameras, side-scan sonar, sediment grabs and cores, acoustic subbottom profiling, and sediment acoustic characterization systems (SACS) (Rhoads, Muromoto, and Ward 1994). The sediment-profile cameras and sediment sampling devices provide descriptions of the benthic environment and sediment texture at points on the seafloor, while the side-scan sonar, subbottom profiling, and SACS provide continuous broad areal maps of the bottom sediment types.

In the benthic resource assessment demonstration, the LLSS provided an additional perspective on the benthos. The high-resolution images of the seafloor with relatively quick coverage rates were effective for classifying sediment types and for assessing fish population densities at specific locations with a level of confidence not seen before.

Some of the steps proposed for LLSS benthic resource assessment would be the same as those used in standard approaches. Traditional trawl and box coring techniques would be used to collect fish and other benthic organisms. The photographic-quality images of fish and benthic organisms recorded by the LLSS would provide additional information on the distributions of those organisms in relation to their habitat. Traditional sampling techniques would provide ground truth information for the LLSS and allow identification of imaged organisms in the LLSS images to familial, generic, or species level depending on image quality.

5 Post-Survey Analysis

Overview

All data are recorded on high band pass videotape or SVHS. Video capture (frame grabs) are the processing "units" for SM2000 images. For mapping purposes, it is desirable to produce an areal mosaic of the bottom if scanning transects are adjacent to one another with some transect overlap. A TARGA-64 video capture card, driven by a 486 PC is used to capture frames for construction of mosaics. Alternatively, a 250 MB RAM high performance Macintosh system operating PHOTOSHOP® processing software can be used to produce mosaics, again utilizing frame grabbing from video data and manual reconstruction within the software and display capabilities of the computer system. A DEC J300 multimedia card, driven by a DEC Alpha 3000-600 UNIX workstation, is used for automated capture of frames to generate linear mosaics along single transects. The objective of video capture is to reduce tens of hours of videotaped data into a compact format and to provide ready access to the geographic, depth, and interpretive information associated with any particular laser image. With the J300 board, it is possible to automate capture of one video frame every 3 sec. Frames are stored in JPEG compressed format, each frame requiring about 35 KB of disk space. Each image is time tagged so that it can be subsequently matched to navigation data. For example, it is possible to reduce 40 hr of video data (25 video cassettes) to about 43,000 usable images copied onto three CD ROM disks.

Data Products

Data output consists of picture quality panoramic analog SVHS video or digital image mosaics of the seafloor. These "lasergrams" are useful for surveying of both soft bottom and hard bottom habitats. The footprint of dredged material can be mapped as well as sediment type, bottom dwelling fish, crabs, lobsters, and dumped structures such as waste barrels. The high optical resolution of the LLSS often allows taxonomic identification of imaged organisms and therefore this technology has potentially important applications for fisheries resource assessment.

A standardized post survey analysis format has not been established to date. However, methodologies exist for frame-by-frame analysis of towed

film camera/video systems. The following sample analysis is intended to show how this protocol may be applied to extracting, quantifying, and displaying LLSS data.

An Example of Post-Cruise LLSS Image Analysis

Post-cruise analysis of images of the seafloor is usually focused on quantification of recognizable organisms and/or categorization of seafloor characteristics (either natural and/or anthropogenic). Many of the studies utilizing visual images are oriented towards assessing megafaunal (organisms large enough to discern on visual images) distributions and identifying factors (physical and biological) that control them (Grassle et al. 1975; Hecker, Blechschmidt, and Gibson 1980; Hecker et al. 1983; Blake et al. 1985, 1987; Maciolek et al. 1987a, 1987b; Langton and Uzmann 1989; Langton et al. 1990; Hecker 1990, 1994; Auster et al. 1991; Hecker Environmental Consulting 1992; Malatesta, Auster, and Carlin 1992). To accomplish this objective, continuous images are usually divided into a number of discrete intervals, that can be treated as samples in subsequent analyses. Several different approaches may be utilized in dividing the LLSS video images into quantifiable samples depending on the issue being addressed and how fine the detail desired. One approach is to analyze the video images by "time intervals" (i.e., minute intervals), and then count and identify all organisms and seafloor features of interest observed within each interval. One major drawback of this approach is that the resulting spatial resolution is frequently too coarse to discern habitat features on a scale that is important to individual organisms (i.e., crossing habitat boundaries). Another approach would be to analyze an equal number of randomly selected frames from different locations within the survey area. However, this randomization approach results in a substantial loss of faunal/habitat information. The greatest quantity of information per transect can be obtained from images by doing a systematic analysis of individual, non-overlapping, contiguous frames ("frame-by-frame") of either the entire videotape or selected segments.

All three approaches allow for standardization of area viewed such that faunal densities can be estimated in different locations of the area of interest. Individual frame analysis of the latter two approaches allows for finer detail in assessing faunal associations with dredged material or other seafloor characteristics. All three approaches require the LLSS vehicle to be towed at a constant altitude such that image resolution is comparable among areas being compared. Review of the MBDS LLSS survey collected during the spring 1993 survey indicates that an altitude of 10 ft or less is optimum for identification of many of the larger organisms (Inglin 1994a). Additionally, the "time interval" approach would only be successful if towfish speed is kept constant throughout the survey, so that the area covered is comparable among transect intervals.

Equipment required for analysis of the LLSS video is a high-resolution video monitor, a tape deck with multiple heads such that images are not degraded during freeze framing and slow motion, and a computer for direct

data entry into a database. A video editing system with single frame advance capabilities will substantially speed up data processing and result in greater repeatability if a segment of tape should need to be reviewed.

A frame-by-frame analysis was conducted on a 15-minute segment of video collected during the MBDS survey on April 26, 1993 (Figure 9). To illustrate how this type of methodology might be utilized for post cruise analysis of LLSS video, the results were tabulated for each frame (Appendix A) and presented in graphical form (Figures 10-13). This was accomplished by forwarding in slow motion and "freeze-framing" when the top of the previous frame was at the bottom of the present frame. Recognizable organisms and seafloor characteristics were then tallied for each frame. Additionally, fish trails (sediment clouds marking the abrupt departure of demersal fish) and burrows were also counted as they also are indicators

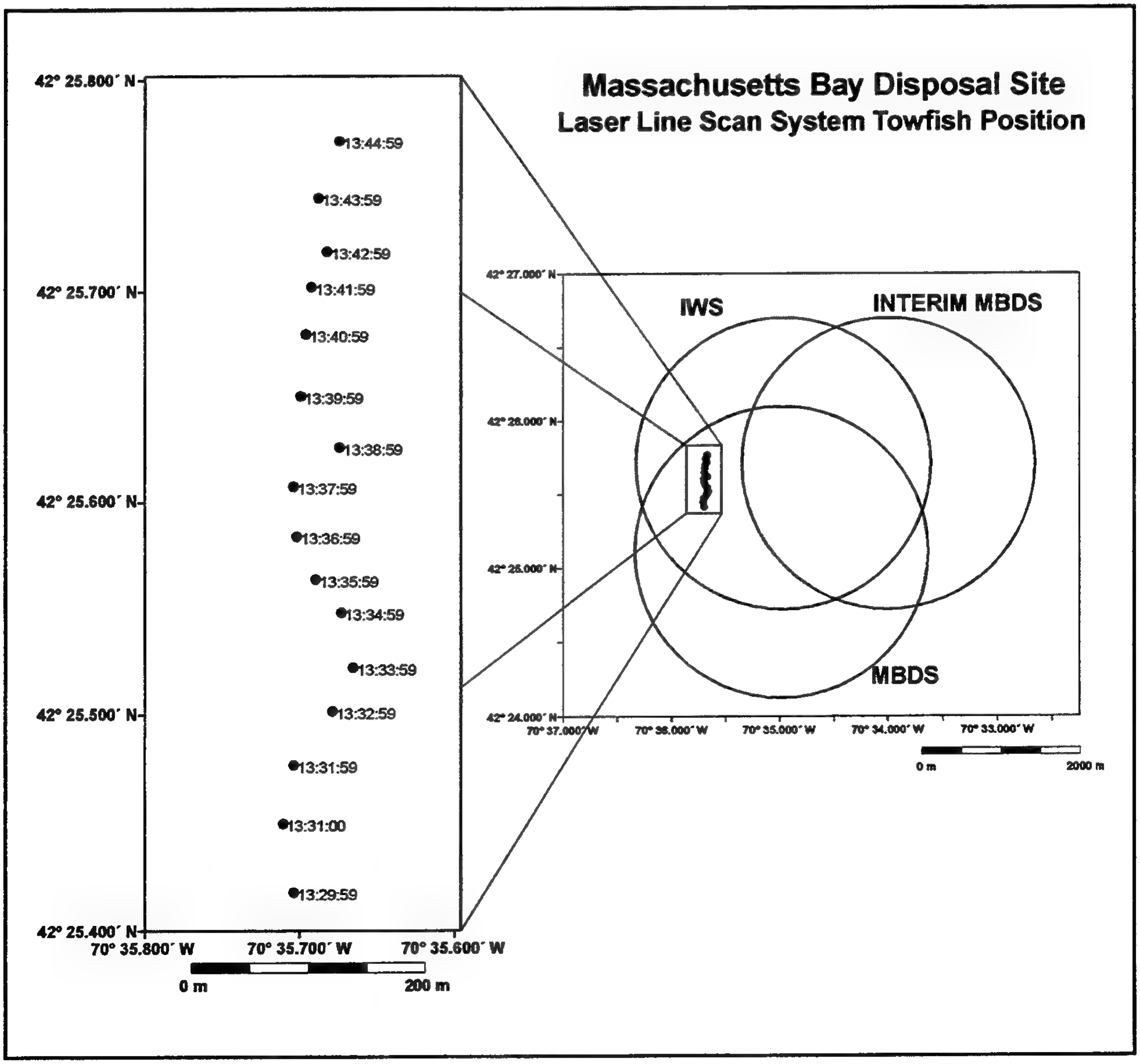

Figure 9. Location of the MBDS LLSS transect segment analyzed in this report

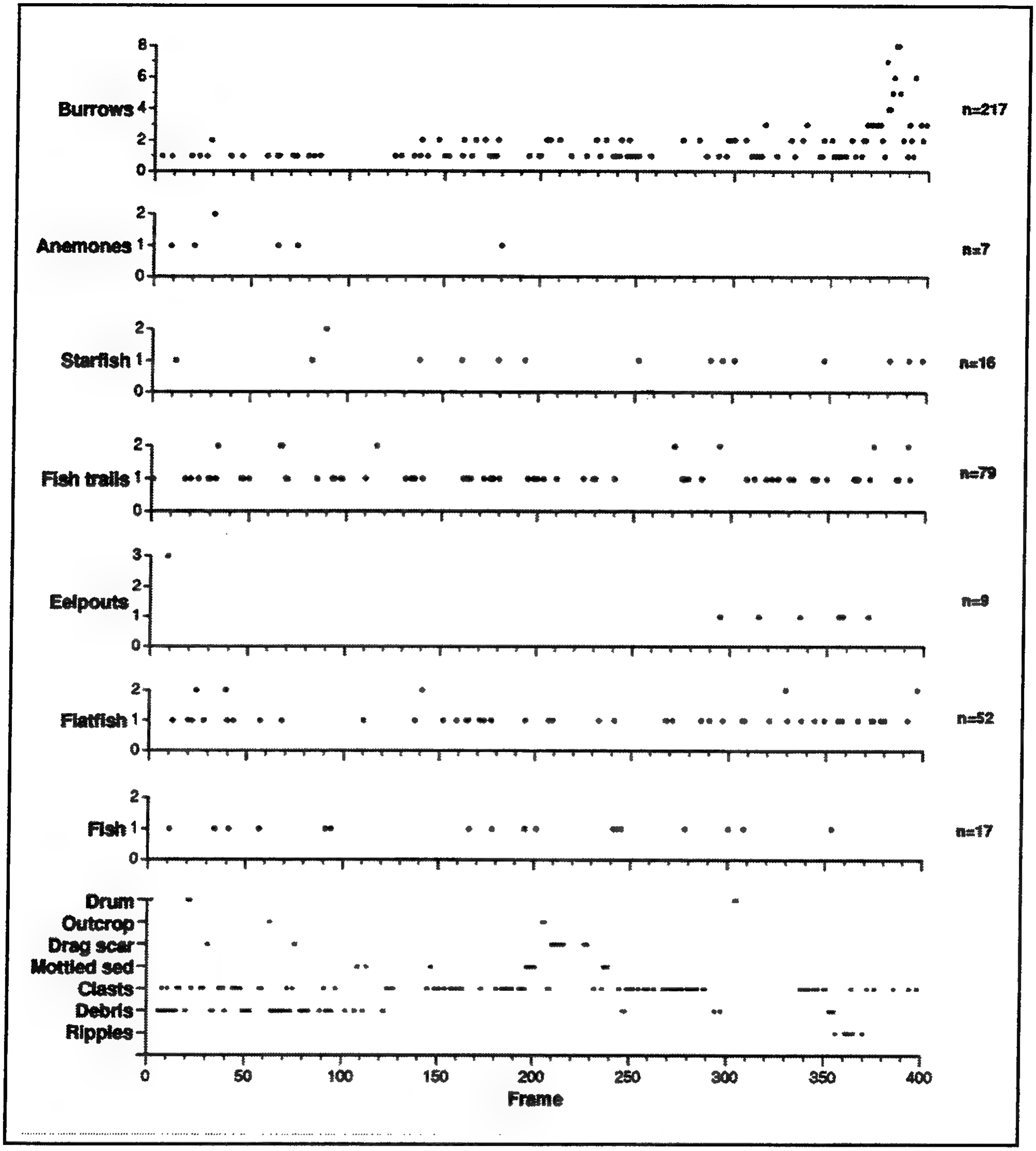

Figure 10. Scatter plots of the abundance of dominant taxa, fish trails, and burrows along a transect in the MBDS. Data based on individual video frames. Seafloor characteristics and human artifacts are also shown

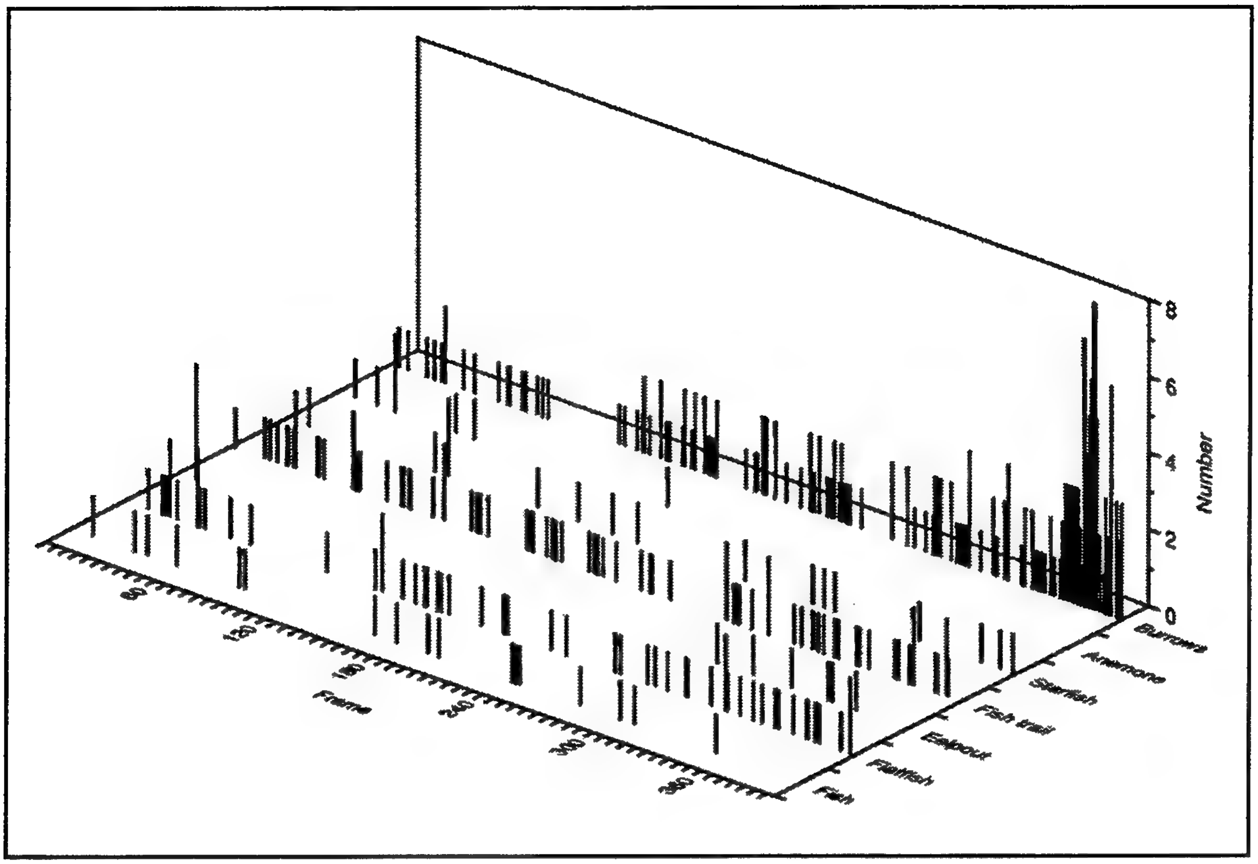

Figure 11. Three-dimensional stick plot of the abundance of dominant taxa, fish trails, and burrows along a transect in the MBDS. Data based on individual video frames

of biological activity. Unfortunately, the altitude and speed over ground of the LLSS vehicle was not constant, so the data have limited value in terms of absolute quantification. However, they can be used for illustrative purposes of the types of graphic data products that can be generated during post-cruise analysis. Where applicable, final data products from other surveys with a towed-camera system will be presented to illustrate how other types of data products can be generated from more controlled and complete data sets.

The 15-min segment of LLSS video selected from the MBDS survey consisted of 399 contiguous frames. A complete data listing for each of the frames can be found in Appendix A. A total of 107 recognizable organisms were counted: 78 fish (including 52 flatfish and 9 eelpouts), 16 starfish (15 appeared to be *Asterias vulgaris*), 7 anemones (6 appeared to be *Cerianthus borealis*), and 6 other organisms (including squid, a possible sea urchin, and a crab). Seventy-nine fish trails were also counted. The majority of these trails were caused by fish not seen in the video, indicating that actual fish densities are probably double those obtained from fish counts alone. Additionally, 217 megafauna burrows were also noted.

Transect plots of taxa and seafloor characteristics were generated for individual frames and for groups of ten consecutive frames. Scatter plots

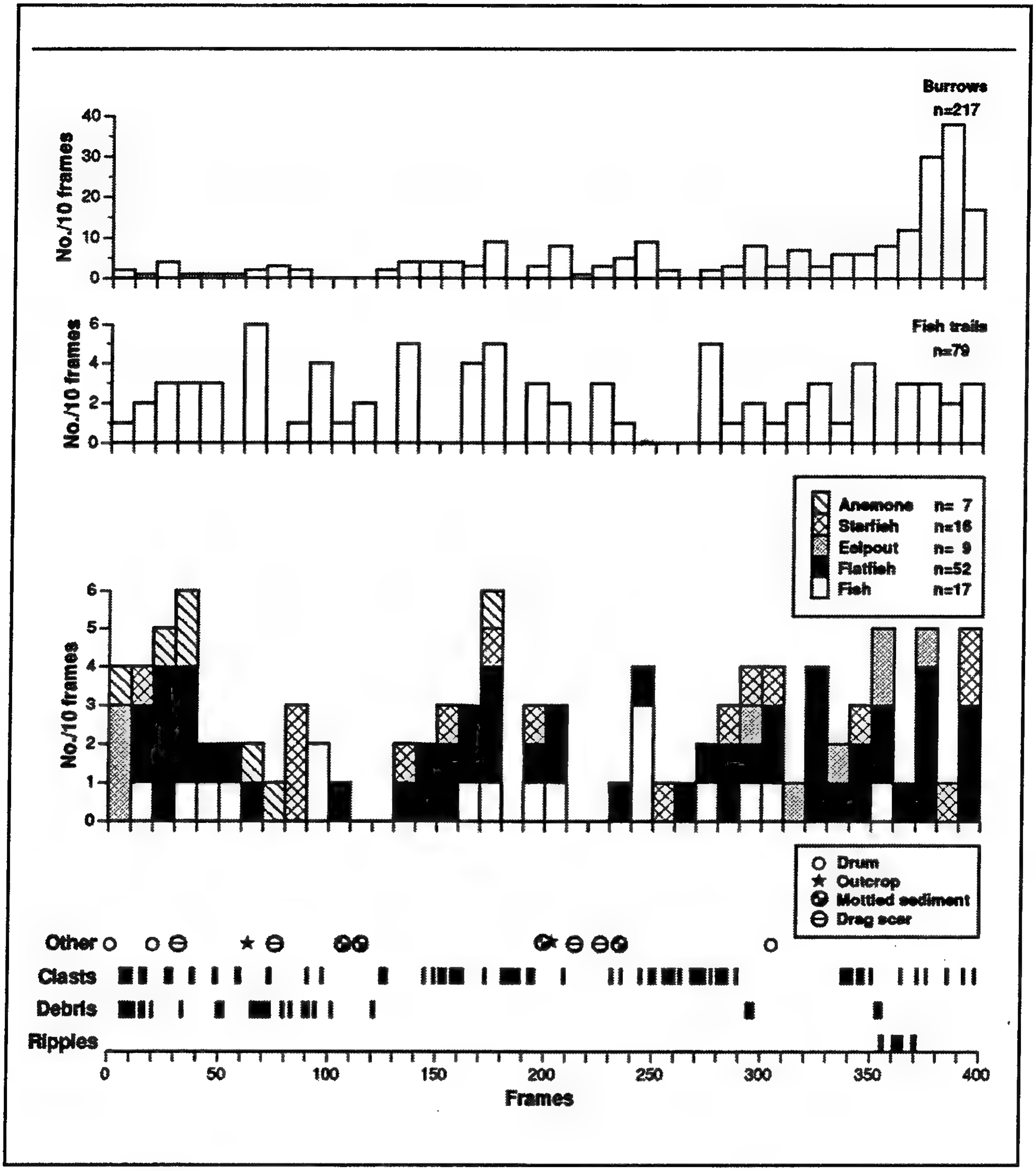

Figure 12. Frequency distributions of dominant taxa, fish trails, and burrows along a transect in the MBDS. Data based on sums from sets of 10 contiguous video frames. Seafloor characteristics are also shown

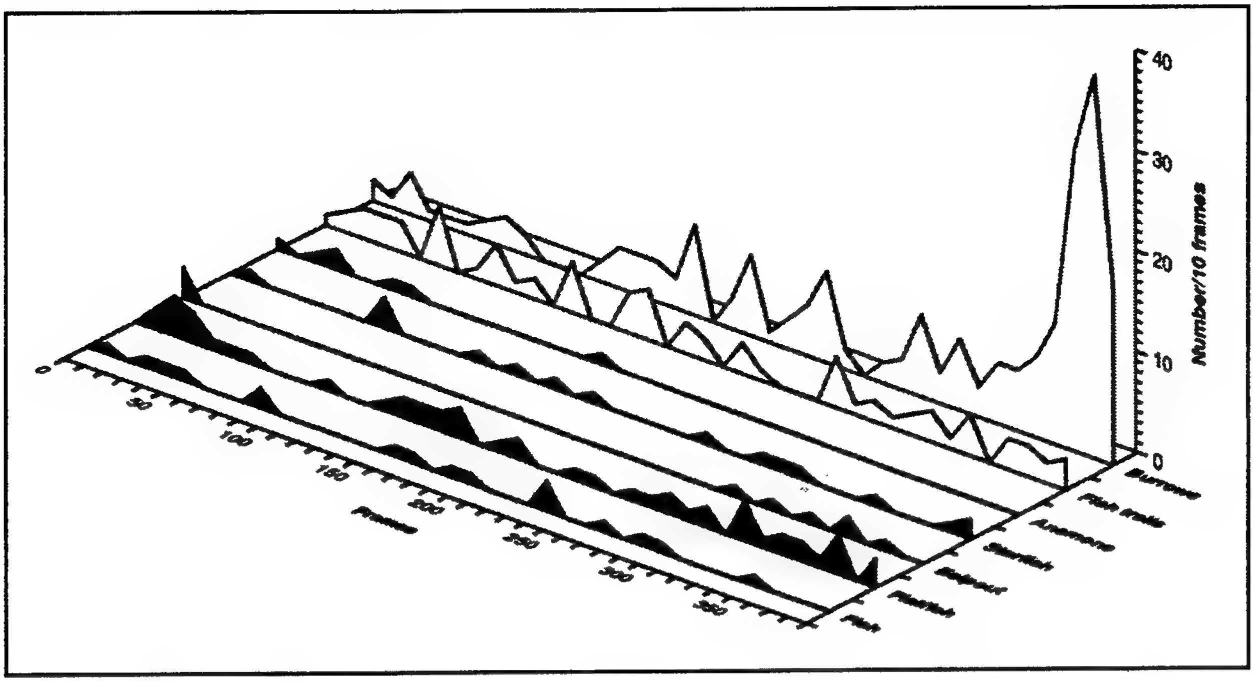

Figure 13. Three-dimensional area plot of the abundance of dominant taxa, fish trails, and burrows along a transect in the MBDS. Data based on sums from sets of 10 contiguous video frames

show the spatial distribution of taxa and seafloor characteristics along the transect (Figure 10). The seafloor along the transect consisted of fine sediment with small-scale biogenic microtopography (i.e., animal tracks, small mounds) indicating an absence of strong currents. Partially buried clasts of sediment (probably old dredged material) were noted throughout most of the area. Debris was also commonly observed in the first third of the transect. Most of it appeared to be construction debris, including telephone poles, wood sticks and planks, rope, chains, an anchor, and numerous partially buried unidentified objects. Three broken 55-gal drums were also noted. Adjacent to one of these drums was a scour mark and an area of lighter colored sediment. Several drag scars (possibly degraded trawl tracks), and areas of mottled light and dark sediment, were also noted. Two small, low-relief outcrops were noted in the first half of the transect and an area of sand-starved ripples was noted near the end of the transect.

Fish and fish trails were seen throughout the area surveyed. Only eelpouts appear to be strongly aggregated, with three occurring in one frame near the start of the transect and the remaining six occurring in individual frames in the last quarter of the transect. Anemones were only seen in the first half of the transect, while starfish were seen throughout. Burrows were seen throughout the transect, but were more abundant towards the end. The distribution of none of these organisms appeared to be strongly influenced by the observed physical characteristics of the seafloor.

A three-dimensional stick plot is a visual summary of faunal distributions along the transect (Figure 11). If different habitats were identified

along the transect, habitat boundaries and sedimentary characteristics could be delineated along the category axis (lower left axis).

To highlight trends in the data by reducing scatter, frames can be pooled into sets of an equal number of contiguous frames. A stacked frequency distribution plot of fauna along the transect is based on pooled sets of ten contiguous frames (Figure 12). Seafloor characteristics and the distribution of fish trails and burrows are also shown. One feature that is immediately evident on this plot is that two areas of 20 frames each were totally devoid of fauna. This was not nearly as evident in the plots based on individual frames. Reasons for the lack of fauna in these areas are not readily apparent. The trend of increased burrow activity toward the end of the transect is also highlighted by pooling frames. A three-dimensional area plot for fauna along the transect based on pooled frames is a visual summary of faunal distributions along the transect (Figure 13).

Examples of other types of graphic and analytical techniques that can be applied to data collected from an LLSS video frame-by-frame analysis are presented from an analysis of still photographs obtained during a towed camera-sled survey off the coast of California (Hecker Environmental Consulting 1992). This study consisted of an analysis of camera-sled transects conducted at a proposed U.S. Navy ocean disposal site (NODS) at 3,000 m depth off the Farallon Islands. A stacked area plot of faunal density along one of three transects conducted in the NODS is based on pooled sets of 20 consecutive frames (Figure 14). All three transects showed similar faunal distribution patterns, indicating a consistent pattern within the site. This finding during the baseline data phase would allow assessment of possible impacts and habitat change due to subsequent disposal.

Another type of graphic that can be generated from the frame-by-frame data is a faunal map of dominant taxa. In a faunal map of the NODS, dominant taxa, the size of sea-pen beds and seafloor characteristics were plotted along each of the transects (Figure 15). This map was based on individual picture frames. If it had been based on pooled sets of picture frames, some of the detail would have been lost. This type of map is a good spatial summary of the distribution of individual taxa within a study area.

Multivariate pattern recognition is another type of analysis that can be conducted on data collected from the LLSS video. This type of analysis is commonly known as community analysis in that it seeks to identify recurrent patterns in species associations (faunal communities). A number of types of community analysis techniques utilizing different analytical strategies are available (Gauch 1982). One such technique is hierarchial classification, which groups samples with similar species composition and/or species with similar spatial distributions. Classification consists of a pairwise comparison of the species composition of all samples (or the distribution of all species) using one of a number of similarity coefficients. Samples (or species) are then clustered such that similar samples (or species) are closer together and dissimilar ones are further apart. Due to low faunal densities, sets of consecutive photographs are usually pooled to provide adequate sample sizes and reduce spurious data. Classification of species is particularly useful by providing species groups that help delineate faunal differences between clusters. Community analysis is valuable in objectively

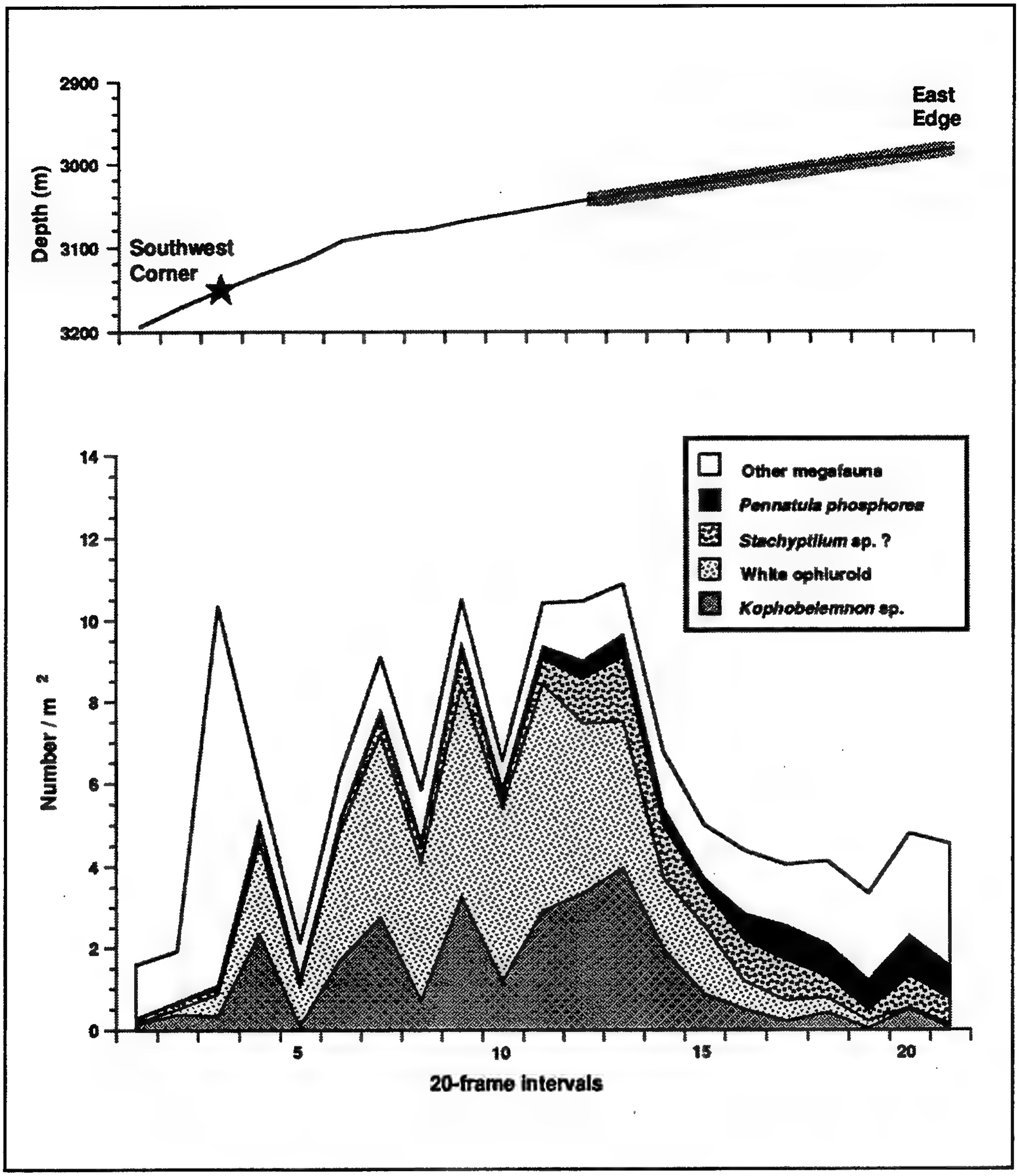

Figure 14. Stacked area plot showing density of total megafauna and four common species for sets of 20 consecutive frames along a camera sled transect within a proposed NODS at 3,000 m depth off California (from Hecker Environmental Consulting (1992)). Depth along the transect is also shown. Shaded area on upper figure is area of debris flow in Figure 15

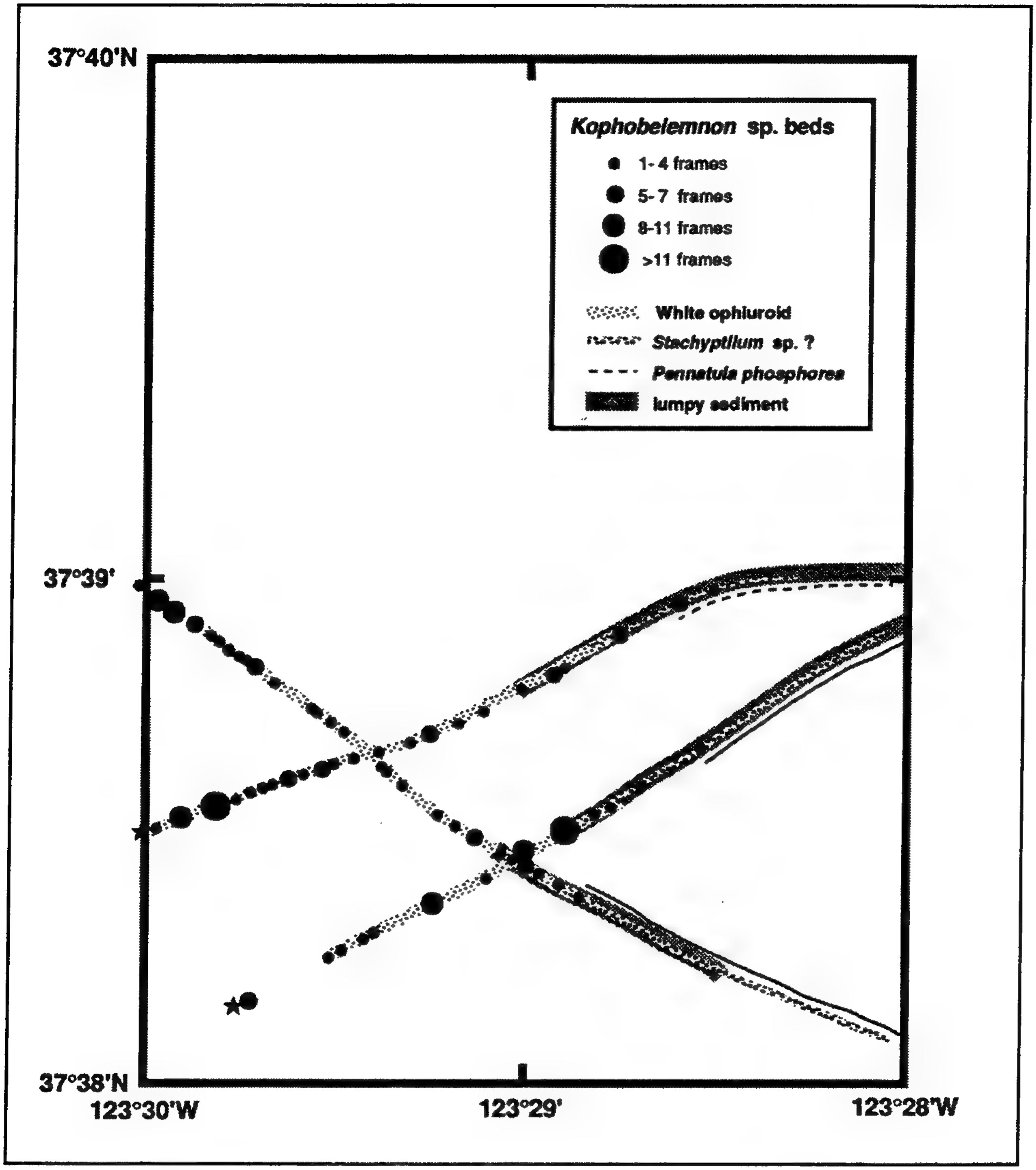

Figure 15. Map of seafloor physical characteristics and dominant species within a proposed NODS at 3,000 m depth off California (from Hecker Environmental Consulting (1992)). Data based on individual frames. Stars represent hard bottom outcroppings

reducing and grouping large data sets, such that major trends in data can be elucidated.

A dendrogram results from hierarchial classification, in this case, using the percent similarity coefficient (Whittaker and Fairbanks 1958) and unweighted pair-group clustering (Sokal and Sneath 1963) of sets of 20 consecutive frames from the NODS survey (Figure 16). The clusters defined by classification were then plotted to provide a spatial map of faunal communities in the NODS (Figure 17). Again, a consistency in faunal patterns can be seen within the site. Habitat characteristics and boundaries can also be shown on the dendrograms and maps.

The analyses described in the above section are mainly of a descriptive nature. Several types of statistical analyses can also be applied to data collected from an LLSS video analysis. One such method was used by Auster et al. (1991), on data from a frame-by-frame analysis of video collected by ROV, to study microhabitat utilization by megafauna. First the frames were sorted by microhabitat (seafloor characteristic) and summaries of species occurrence were generated. Chi-square tests were then conducted for distributions of individual species among the microhabitats. In this test, expected values were weighted for unequal distributions of microhabitats. Where the distributions of taxa were found to be significantly influenced by microhabitat, a Pearson's product moment correlation was computed to discern the direction (positive or negative) of the association. This type of analysis would be particularly useful in discerning differences in species distributions between dredge material and the ambient seafloor. Tables 1 and 2 show the required data summary needed for this type of analysis of the MBDS frame-by-frame video.

Another analysis technique for use on LLSS frame-by-frame video data is suggested by the work of Malatesta, Auster, and Carlin (1992). They developed a nonparametric "randomization" method for analyzing transects of contiguous video frames to test for faunal-microhabitat correlations and sizes of faunal patches. They point out that transect data are usually difficult to deal with statistically because of the lack of independence between quadrats (frames). The authors present a randomization protocol to account for this lack of independence. The Pearson correlation coefficient r is computed from the original data set, then the frames containing the species of interest are randomly permutated and the sample correlation is recomputed. The randomization step is repeated a number of times and the correlation is found to be significant if the randomized values of r exceed the original r in absolute value in a predetermined number of cases. If a correlation exists between a species and a microhabitat, analyses examining faunal patch size must be performed by microhabitat. Subsequent tests for true patch size use the coefficient of dispersion at a sample size of 1 (quadrat) and are recomputed for blocks of 2, 3, ... quadrats for each of the possible start positions of the blocks. The resulting patch size identified by this procedure can be tested for significance by a similar randomization of frames containing the species of interest.

Associations between taxa can be examined by a 2 X 2 contingency table and Cole's measure of association (Poole 1974). As an example of this type of analysis, the association between fish and fish trails was examined

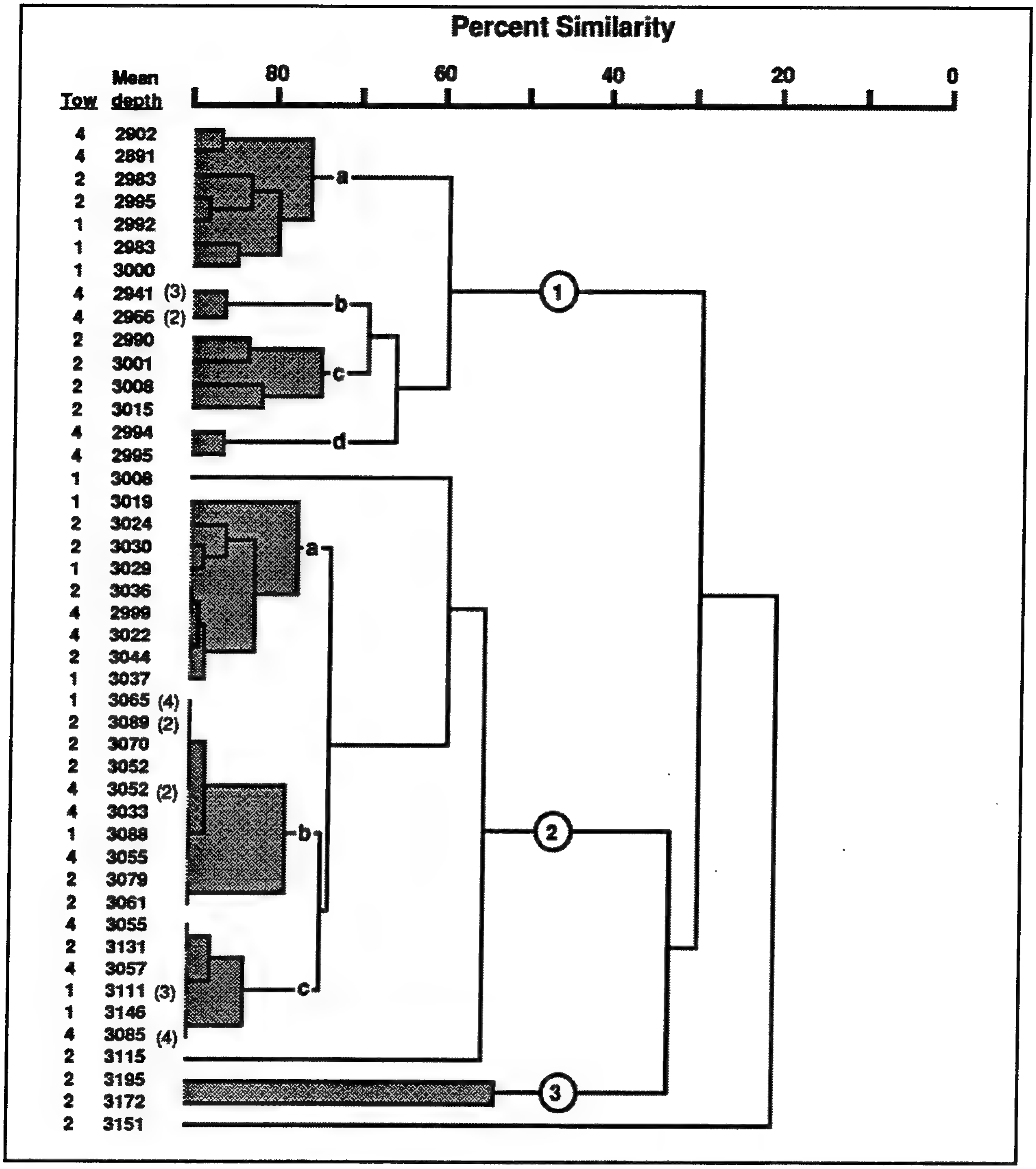

Figure 16. Dendrogram resulting from heirarchial classification of sets of 20 consecutive frames within a proposed NODS at 3,000 m depth off California (from Hecker Environmental Consulting (1992))

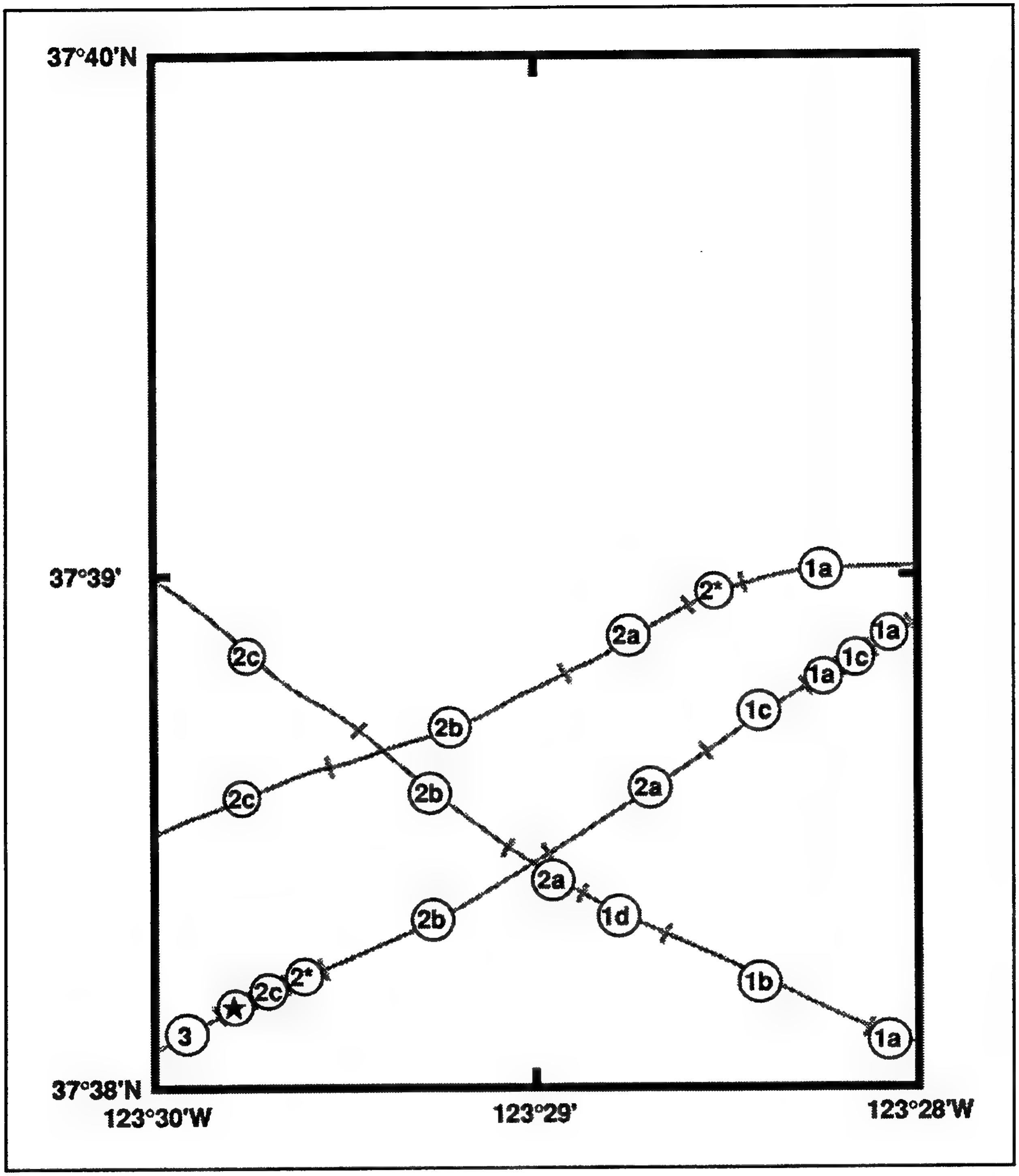

Figure 17. Map of cluster groups defined by heirarchial classification plotted along camera-sled transects within a proposed NODS at 3,000 m depth off California (from Hecker Environmental Consulting (1992))

Table 1
Summary of Abundance of Taxa Observed in Frames with Different Seafloor Characteristics[1]

Taxa	Seafloor Characteristics				
	Sediment (n = 226)	Anthropogenic Debris (n = 50)	Buried Clasts (n = 85)	Miscellaneous (n = 35)	Total (n = 399)
Fish	9	3	4	1	17
Flatfish	35	6	7	4	52
Eelpout	5	3	0	1	9
Starfish	7	3	6	0	16
Anemone	1	4	0	2	7
Other	4	1	1	0	6
Fish Trail	49	14	11	5	79
Burrow	156	11	25	25	217

[1] Data from a frame-by-frame analysis of a 15-min video segment from the MBDS LLSS survey.

Table 2
Percent of Taxa Observed in Frames with Different Seafloor Characteristics[1]

Taxa	Seafloor Characteristics			
	Sediment (57%)	Anthropogenic Debris (13%)	Buried Clasts (21%)	Miscellaneous (10%)
Fish	53	18	24	6
Flatfish	67	12	13	8
Eelpout	56	33	0	11
Starfish	44	19	38	0
Anemone	14	57	0	29
Other	67	17	17	0
Fish Trail	62	18	14	6
Burrow	72	5	12	12

[1] Data from a frame-by-frame analysis of a 15-min video segment from the MBDS LLSS survey.

frame by frame in the MBDS LLSS transect, resulting in the following 2 X 2 contingency table:

	Fish Trail Present	Fish Trail Absent	Σ
Fish present	19	45	64
Fish absent	53	282	335
Σ	72	327	399
X2 = [(19)(282)-(45)(53)]2399/(72)(335)(64)(327) = 6.986			

This chi-square statistic is significant at the 0.01 level of probability, meaning that fish and fish trails are not independently distributed among the frames. The association between fish and fish trails was positive, meaning that both co-occurred at a frequency that was higher than would be expected if there was no association. Cole's measure of association was computed as

$$C1 = [(19)(282)-(45)(53)]/(19+45)(19+53) = 0.645$$

showing that fish and fish trails are partially associated.

Great care should be taken in interpreting the results obtained from some of the statistical analyses mentioned above. Most statistical techniques assume that entities are normally distributed. This is rarely the case in nature and is definitely not the case in most instances of anthropogenic disturbance of the seafloor (i.e., dredged material, construction debris).

A variety of graphic, descriptive, and statistical techniques that can be used to analyze data obtained from LLSS video have been shown. Most of these techniques would be useful in addressing management decisions concerning environmental impacts on the seafloor.

Frame-by-frame analysis of the MBDS LLSS video images presented here required a one person-hour per minute of video. It is anticipated that this time could be reduced by approximately 50 percent with more routine viewing and the use of a video editing system that is capable of single frame advance. A fair amount of time was spent trying to get back to a specific point if a frame was "overshot." Additionally, the video should initially be previewed in slow-motion forward to develop categorization criteria and numerical codes for a library of seafloor targets of interest. Automatic data entry of vehicle altitude, swath width, and towfish coordinates from the shipboard control console files into the post analysis database would also speed up the analysis process. Consistency of data quality would also be facilitated by viewing the film in two-person teams, with one person reading the image while a second person enters the data into the computer.

6 Comparison with Other Towed Imaging Systems

Side-Scan Sonar

Side-scan sonar imaging systems have the highest range and lowest resolution of all existing towed imaging systems (75-300 m wide, 1- to 5-m resolution). Although they are not optical imaging systems, improvements in signal processing and data display allow side-scan sonars to produce corrected "optical-like" images of large areas of the seafloor. They are particularly well-suited for reconnaisance surveys defining broad characteristics of sediment type and distribution of large objects (e.g., rock outcrops, sunken scows, industrial debris). Of particular note for this review, side-scan sonar has shown great facility under some conditions for distinguishing historical and fresh dredged material mounds from ambient seafloor (SAIC 1995) . Because side-scan sonar is an acoustic sensor, discrimination of sediment types (including dredged materials) is dependent on variations in surface roughness and acoustic density (water content, sorting, grain size). Individual disposal mounds (e.g., from a hopper dredge) can be detected on the seafloor for decades after their disposal. The distinctive circular impact patterns can often be discerned more easily than other, less regular variations in sediment type.

Due to the order of magnitude difference in range and resolution between side-scan sonar and the optical towed imaging systems discussed below, it is best to consider the side-scan sonar as an appropriate reconnaisance tool for planning detailed imaging surveys. Side-scan sonar can be used in conjunction with narrow-beam fathometers to rapidly produce a three-dimensional map of surface texture with complete coverage of the survey area. All towed systems must remain near the seafloor to get optimal resolution, yet the danger of unexpected obstacles or rapid changes in slope place limits on tow height. Preliminary surveys that produce three-dimensional maps (texture on relief) are very helpful in defining tow heights, survey lanes and directions prior to optical surveys. The authors strongly recommend preliminary wide-area surveys with side-scan sonar and a narrow-beam fathometer prior to any optical surveys.

Video Camera Sleds/ROVS

Video cameras mounted on towed sleds, towed,or tethered ROVS provide an intermediate resolution with limited range (1- to 6- ft width, 1- to 10-cm resolution). They are best deployed in clear water over an undisturbed seafloor. Under optimum conditions, these systems have the advantages of relatively low-cost deployment, manueverability, and real-time observation. For close-range object inspection, especially in depths beyond the compressed-air diving range (>90 ft), a manueverable ROV with a video camera can be highly effective. These systems have been used successfully to investigate hazardous waste barrels (Section 4.2, Wiley et al. (1992)) after location of the targets with side-scan sonar. Such an approach is common, and often effective in investigation of deep shipwrecks. However, as pointed out in Section 4.2, ROV or sled-based video can be a time-consuming approach and the resolution and field of view of video cameras is, at present, extremely limited (see Table 3).

Table 3
Comparison of LLSS Technology with Other Seafloor Imaging Systems[1]

Platform/Sensor	Advantage	Disadvantage	Estimated Cost
LLSS	High optical range and resolution in coastal waters, survey speed	Size, weight	\$15,000/n.m.[2]
Side-scan sonar	Ideal for turbid water and rate of bottom coverage, low cost	Low object resolution, especially <1 m in size	\$1,500/n.m.[2] 50 ft vessel, \$2,850/day
Video sled	Moderately high optical resolution, maneuverable if ROV included in tow sled	Rate of coverage is low, imaging range low in turbid water	\$550,000/n.m.[2] 50 ft vessel, \$2,950/day Video sled (not ROV)
Film sled	Highest optical resolution	Size, weight. Rate of coverage is low, imaging range low in turbid water, does not collect continous coverage	\$600,000/n.m.[2] 100 ft vessel, \$3,450/day Large bulk film sled

[1] Costs include vessel, equipment, personnel, and operating costs but not data processing.

Film Camera Sleds

Film cameras mounted on towed sled frames have the highest potential optical resolution of all existing towed imaging systems (Table 3). The potential for high quality images is best realized in oligotrophic open ocean waters where suspended particle densities are low. For example, the Benthic Apparatus for Biological Surveys has been used successfully in baseline characterization and post-disposal site surveys at the Navy 103 disposal site near the Farallons off the central California coast in 3,000 m of water (Hecker 1992). In such instances, imaging fields of 5 m^2 are possible with coverage rates of ca. 1 km/hr. Nevertheless, high suspended

loads can develop in deep water related to benthic "storms." High concentrations of marine "snow" in nepheloid layers near the bottom can make film camera imaging impractical in otherwise optically clear deep water. Because nearshore benthic environments are commonly correlated with high particle loads, light scattering seriously compromises image quality and the full potential of film cannot be realized. Exceptions to this generalization exist in the coastal waters of Hawaii and in unpolluted Caribbean Island environments.

Estimation of Comparative Costs and Advantages of Towed Imaging Systems

Each system has different requirements for vessel support, operating range, and conditions. In order to provide an estimation of relative costs, a typical task requirement has been selected for evaluation (Table 3). It is assumed that each system would be used to survey an area of seafloor 1 nautical mile square (n.m.^{2}) located at 25 m depth in moderately turbid coastal waters in the northeastern United States. While this is a large area to survey comprehensively with a video sled, it is a reasonable objective for a coastal District to consider for site designation, baseline or post-disposal monitoring. A typical use of most imaging systems would be to sample the area with widely spaced transects and correlate with comprehensive side-scan sonar coverage. The side-scan sonar range used here is for high-resolution target identification, not comprehensive coverage. Coverage rates have been calculated assuming 10-min turns between lanes. Coverage rates would increase with longer lanes. Assumptions used to provide coverage rates and cost estimates are presented in detail in Appendix B.

7 Future LLSS Developments

The LLSS described here has certain limitations that may be mitigated or eliminated in future development. For example, the LLSS is currently limited to a totally in-water monochromatic light path and senses only reflectivity and bottom texture to produce a two-dimensional image. The relatively slow scanning speed of the laser over the bottom requires that the towfish be stable to eliminate geometric distortion of the inbound image. Further, in shallow water with high ambient light scattering, nighttime surveys are required.

Developments are currently under way to build a DFI LIDAR that will be capable of both reflectance and multispectral fluorescence imaging using a pulsed time gated laser beam so that the sensor is insensitive to both ambient light and platform motion. This system can also be range-gated to produce three-dimensional images from either an airborne or towed in-water platform. Because this development project involves proprietary technology, details of the system cannot be revealed at this time. The point of contact for this program is Dr. Gregory Mooradian, project manager, Sets Technology, Inc., 300 Kahelu Avenue, Suite 110, Mililani, HI 96789, (808) 625-5262. Field tests of this system are expected to take place by the end of 1996.

The benefits of DFI over the existing LLSS technology are obvious, especially if survey costs are comparable. The main technological benefit will be that the DFI image will be able to be spectrally analyzed. In addition to acquiring a two-dimensional image, each pixel in the field of view can potentially spectrally discriminate and classify objects and features of interest. With range gating, this can be done in the third dimension (e.g., spectral analysis of different levels within suspended sediment plumes, ambient water column, or vertical gradients in sediment quality on the flanks of a disposal mound). Biological features may also be spectrally identified yielding more information about species than is currently available from conventional LLSS based on size and morphology alone. In addition, DFI will potentially yield totally new biological/ecological/pollutant data through spectral identification of detrital phytoplankton pigments on the bottom, chlorophyll in living algae and submerged rooted vegetation (SRV), and negatively buoyant oil on the bottom.

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Appendix A
Frame-by-Frame Analysis Data from a 15-Min Video Segment, MBDS LLSS Survey

Frame	Time	Altitude	Width	Comments	Fish	Flatfish	Eelpout	Starish	Anemone	Other	Fish trail	Burrow	Notes
1	133001	8.2	9.3								1		
2	133001	7.6	8.7	buried drum									drum on side
3	133004	7.6	8.7										
4	133007	7.3	8.8									1	dark ? re
5	133007	7.5	9.2										
6	133010	7.5	9.2	large clast & rope									white ? ulc
7	133013	7.6	8.6	buried clast & debris									
8	133013	7.3	8.3	buried clasts									
9	133016	6.8	8.1	buried debris & boulder			3		1			1	anemone is Cerianthus, lg burrow
10	133019	6.8	8.1	buried debris									rough bottom
11	133019	6.4	7.2	buried clasts	1								
12	133022	7.7	8.8	construction debris		1		1					
13	133025	7.7	8.8										? re
14	133028	6.8	8.6	buried clasts & debris									
15	133028	7.1	8.3	buried clasts & debris									
16	133031	7.1	8.3	buried clasts									
17	133033	7.1	8.0	buried clasts							1		? lrc
18	133033	8.6	9.8										? center
19	133037	8.6	9.8									1	
20	133040	8.8	9.7	buried clasts & anchor		1					1		
21	133040	8.6	10.3	buried drum, broken					1				drum on side, anem on drum, dark ? lrc
22	133043	8.6	10.3	broken drum		1							
23	133045	8.2	9.4	buried clasts								1	
24	133045	8.1	9.2			2					1		
25	133048	8.3	9.8										
26	133051	8.3	9.8										
27	133051	8.4	9.6									1	
28	133054	8.7	9.9	buried clasts		1							
29	133057	8.7	9.9	buried clasts							1	2	
30	133057	8.8	9.8								1		
31	133100	9.0	10.2	drag scar					2				anemones are Cerianthus
32	133103	9.0	10.2										
33	133103	8.3	9.4	buried chain							1		
34	133106	7.4	8.4	buried chain	1						2		
35	133109	7.4	8.4										
36	133112	6.7	8.3										? re
37	133112	8.8	9.5	buried clasts									
38	133115	8.8	9.5	buried clasts									
39	133118	8.8	9.9	buried clasts		2						1	
40	133118	7.7	8.8	rope?		1							
41	133121	7.7	8.8		1								fish is eel
42	133124	7.0	8.0										dark alt change
43	133124	7.5	8.6			1							
44	133127	7.5	8.6	buried clasts									
45	133130	8.7	10.0									1	
46	133130	9.2	10.5	buried clasts							1		

LEGEND	
l	left
r	right
e	edge
ll	lower left
lr	lower right
c	center
u	upper

Frame	Time	Altitude	Width	Comments	Fish	Flatfish	Eelpout	Starfish	Anemone	OtherFish	trail	Burrow	Notes
47	133133	9.2	10.5								1		?debris? ur
48	133133	9.7	10.4	buried clasts									shadow? ul
49	133136	9.7	10.4	construction debris									large piece wood
50	133139	9.4	10.7	buried clasts & debris							1		
51	133139	9.2	10.5	debris									
52	133142	9.2	10.5	construction debris									
53	133145	8.9	10.2	construction debris									
54	133145	8.4	9.6							1			squid
55	133148	8.4	9.6										
56	133151	10.6	12.2										
57	133151	9.5	10.2		1	1							
58	133154	9.8	11.0	buried clasts								1	
59	133137	9.8	11.0	buried clasts									
60	133157	8.3	9.5										
61	133200	9.3	10.7										
62	133203	9.3	10.7										
63	133206	9.6	10.8	subcrop								1	
64	133206	9.3	10.6	buried debris					1			1	
65	133209	9.6	11.0	buried debris						1			? ulc - anemone? or urchin?
66	133212	9.6	11.0	buried chain							2		v dark ? ue
67	133212	8.5	9.7	buried chain							2		
68	133215	7.6	9.9	buried debris		1							partially buried sheet
69	133218	7.6	9.9	buried debris							1		partially buried sheet
70	133221	8.3	9.1	buried debris							1		wood
71	133221	9.3	10.7	buried debris								1	
72	133224	9.3	10.7	buried clast									
73	133227	10.0	11.4	construction debris								1	telephone pole
74	133227	10.1	11.6	construction debris					1				anemone on telephone pole
75	133230	8.0	9.1	buried clast									
76	133233	8.0	9.1	drag scar									
77	133233	6.3	9.4										? umc
78	133236	9.3	10.0										
79	133239	9.3	10.0	debris								1	
80	133242	9.3	10.7	debris									
81	133242	8.4	9.7	lg clast?									
82	133245	8.5	9.7					1				1	
83	133246	8.5	9.7	buried debris									
84	133248	7.1	8.2										
85	133250	9.0	10.0								1	1	stick
86	133254	8.9	10.1										
87	133256	8.9	10.1										stick
88	133256	9.1	10.9										
89	133259	8.9	9.6	construction debris				2					2 diff sp SF on telephone pole
90	133302	8.9	9.6										
91	133305	8.6	9.9	buried clasts	1								fish is eel
92	133305	8.6	9.8	debris									
93	133308	8.6	9.8								1		?mr
94	133311	9.5	10.9	buried debris	1						1		
95	133311	11.1	12.6	construction debris									telephone pole
96	133314	11.1	12.6										

LEGEND	
l	left
r	right
e	edge
ll	lower left
lr	lower right
c	center
u	upper

Frame	Time	Altitude	Width	Comments	Fish	Flatfish	Eelpout	Starish	Anemone	OtherFish	trail	Burrow	Notes
97	133317	10.3	11.8	buried clasts									
98	133317	12.3	14.0								1		
99	133320	12.3	14.0								1		
100	133323	11.7	13.4										
101	133323	11.5	13.1										
102	133326	13.4	15.3	buried debris									
103	133329	13.4	15.3										
104	133332	12.5	13.9										
105	133332	12.6	14.4										
106	133335	12.6	14.4										
107	133336	12.0	13.8	buried debris?									
108	133341	12.5	14.3	dark streaks on sed									
109	133341	12.1	13.1										
110	133344	12.1	13.1										
111	133347	12.4	13.9	buried ??		1					1		
112	133337	11.0	12.6										
113	133350	11.7	13.4	mottled sed									
114	133353	11.7	13.4										
115	133353	11.9	12.7										
116	133356	12.2	14.2										
117	133359	12.2	14.2								2		
118	133402	13.5	15.5										
119	133402	13.5	14.3										
120	133405	13.9	15.3										
121	133408	13.9	15.3										
122	133411	12.3	14.0	buried debris									
123	133411	11.4	13.0										
124	133414	11.4	13.0	buried clasts									
125	133417	10.2	11.2									1	
126	133417	9.4	11.0	buried clasts									
127	133420	9.6	11.0	buried clasts									
128	133423	9.6	11.0									1	
129	133423	10.1	11.5										
130	133426	10.1	11.5										
131	133429	10.1	11.5										
132	133432	11.9	13.9								1		
133	133435	10.0	11.4										
134	133435	10.8	12.4										
135	133438	8.4	9.6								1	1	
136	133441	8.4	9.6								1		
137	133444	8.6	9.9			1				1	1		whelk
138	133444	8.3	9.5									1	
139	133447	8.3	9.5					1				2	
140	133450	9.4	10.7										
141	133453	9.0	10.3	small scale rough surf		2					1		
142	133453	10.6	12.2									1	v dark cloud rc
143	133456	10.7	12.2										
144	133459	10.7	12.2										
145	133459	11.8	12.8	buried clasts									
146	133502	11.6	13.1										

LEGEND

l	left
r	right
e	edge
ll	lower left
lr	lower right
c	center
u	upper

Frame	Time	Altitude	Width	Comments	Fish	Flatfish	Eelpout	Starish	Anemone	OtherFish	trail	Burrow	Notes
147	133505	11.6	13.1	mottled sed								2	
148	133508	9.6	10.9										
149	133508	8.3	9.6	buried clasts									
150	133511	7.1	8.9									1	
151	133514	7.1	8.9	buried clasts									
152	133514	7.4	8.5	slightly rough sed		1						1	
153	133517	6.7	7.7	small scale rough surf									? lr
154	133520	6.7	7.7	buried clasts									
155	133523	6.1	7.0										dark-alt ch
156	133526	6.6	6.5										? ur
157	133526	7.0	8.0	buried clast									1/2 dark-alt ch
158	133529	7.0	8.0	buried clasts									1/2 dark- alt ch
159	133532	7.3	8.3			1						1	
160	133532	8.5	9.7	buried clasts				1				2	
161	133535	9.4	10.8								1		
162	133538	9.4	10.8	buried clasts									
163	133541	8.0	9.1	buried clasts							1		
164	133541	9.1	10.1			1					1	1	
165	133544	9.1	10.1			1					1		
166	133547	8.2	10.0		1							2	image broken
167	133550	7.6	9.4										
168	133550	7.8	9.0										1/2 dark-alt ch
169	133553	10.8	11.9										dark-alt ch
170	133556	10.8	11.9										
171	133556	8.7	10.3			1						2	
172	133559	9.7	11.0								1		
173	133602	9.7	11.0	buried clasts		1						1	round dark ? uc
174	133605	10.5	12.0									1	
175	133605	9.3	11.5								1	1	
176	133608	9.3	11.5								1	1	
177	133611	8.6	9.8			1					1	1	
178	133611	9.4	10.7		1							2	
179	133614	7.9	9.7					1					
180	133617	7.9	9.7						1		1		anemone is Cerianthus
181	133619	7.8	9.4	buried clasts									
182	133619	8.3	9.4	rough surface - right									
183	133622	7.9	9.1	rough surface - right									dark ? urc
184	133625	7.9	9.1	buried clasts									
185	133628	7.0	7.9										dark-alt ch
186	133628	7.4	8.5	buried clasts									
187	133631	7.4	8.5										
188	133631	7.0	7.9	buried clasts									
189	133634	7.0	7.9	buried clasts									
190	133637	7.8	8.9										dark-alt ch
191	133637	7.2	8.1										1/2 dark-alt ch
192	133640	8.3	9.7										
193	133643	8.3	9.7	buried clasts				1					
194	133643	8.3	9.5									1	
195	133645	7.4	8.9	buried clasts	1	1					1		
196	133649	7.4	8.9	buried clasts									

LEGEND	
l	left
r	right
e	edge
ll	lower left
lr	lower right
c	center
u	upper

Frame	Time	Altitude	Width	Comments	Fish	Flatfish	Eelpout	Starfish	Anemone	OtherFish	Fish trail	Burrow	Notes
197	133652	7.5	9.0	mottled sed									
198	133652	7.9	9.0	mottled sed							1		
199	133655	7.9	9.0	mottled sed								1	
200	133658	8.3	9.5	mottled sed							1	1	
201	133658	7.3	8.3	mottled sed	1								
202	133701	7.3	8.3										
203	133704	7.4	8.5								1	2	
204	133704	7.9	9.1									2	
205	133707	8.2	9.4	subcrop								2	shell
206	133710	8.2	9.4	low relief outcrop									
207	133710	8.8	8.6			1							
208	133713	7.9	9.3	buried clasts									
209	133715	7.9	9.3	buried clasts		1							
210	133715	7.8	8.9	drag scar							1	2	
211	133718	9.5	10.9	drag scar									? lre
212	133721	9.5	10.9	drag scar									
213	133721	9.5	10.9	drag scar									
214	133724	9.9	12.1										
215	133724	9.8	11.2	drag scar									
216	133727	9.8	11.2	drag scar								1	
217	133730	9.9	11.4										
218	133733	9.9	11.4										
219	133733	11.1	12.7										
220	133736	10.4	11.8										
221	133739	10.4	11.8										
222	133730	10.5	12.0										
223	133742	10.3	11.1										
224	133745	10.3	11.1								1	1	
225	133748	10.4	11.9										
226	133748	9.2	10.6										
227	133751	9.2	10.6	drag scar									
228	133754	10.3	12.0	drag scar									
229	133754	9.1	10.0								1	2	
230	133757	8.8	10.1								1		
231	133800	8.8	10.1									1	
232	133800	9.4	10.8	buried clasts									
233	133803	7.9	9.1			1							
234	133806	7.9	9.1									2	
235	133809	7.6	9.6										
236	133809	8.0	9.2	buried clasts									dark-alt ch
237	133812	8.0	9.2	mottled sed									
238	133815	9.1	10.4	mottled sed								1	
239	133815	9.1	10.4	mottled sed								1	
240	133818	8.6	9.8								1		
241	133821	8.6	9.8		1	1						1	
242	133824	8.6	9.8									2	
243	133824	9.2	9.9		1								
244	133827	10.1	10.9										
245	133830	10.1	10.9	buried clasts	1							1	fish is eel
246	133830	10.1	10.9									2	

LEGEND	
l	left
r	right
e	edge
ll	lower left
lr	lower right
c	center
u	upper

Frame	Time	Altitude	Width	Comments	Fish	Flatfish	Eelpout	Starish	Anemone	OtherFish	trail	Burrow	Notes
247	133830	9.9	11.3	buried chain								1	
248	133836	9.4	10.7	buried chain									
249	133836	10.4	11.4	buried clasts								1	
250	133839	9.9	10.7									1	
251	133842	9.9	10.7	buried clasts								1	
252	133845	9.6	11.0	buried clasts				1					
253	133845	11.1	12.7										
254	133848	11.1	12.7										
255	133851	11.0	12.6	buried clasts									
256	133851	11.2	12.7										? dark lle
257	133854	11.2	12.7									1	
258	133857	10.9	12.5	buried clasts									
259	133857	10.5	12.0	buried clasts									
260	133900	12.0	13.7	buried clasts									
261	133903	12.0	13.7										
262	133903	11.4	13.0							1			squid
263	133906	12.2	14.0	buried clasts									
264	133909	12.2	14.0										
265	133912	12.2	14.3										
266	133912	11.5	12.8										
267	133915	11.2	12.7										
268	133918	11.2	12.7	buried clasts		1							
269	133918	12.5	14.3	buried clasts									
270	133921	11.4	12.7	buried clasts									
271	133924	11.4	12.7			1					2		
272	133927	9.3	10.3	buried clasts									
273	133927	9.3	10.7	buried clasts									
274	133930	10.6	11.7	buried clasts								2	
275	133933	10.6	11.7	buried clasts							1		
276	133936	10.0	11.9								1		
277	133936	9.3	10.6	buried clasts									
278	133939	9.3	10.6		1						1		
279	133942	9.0	10.3										
280	133942	7.8	8.9	buried clasts									
281	133945	7.8	8.9	buried clasts									
282	133948	8.0	9.1	buried clasts								2	
283	133948	8.4	9.6	buried clasts									
284	133951	8.2	9.9	buried clasts									broken image
285	133953	8.2	9.9	buried clasts							1		
286	133953	9.1	10.2			1						1	
287	133957	8.3	9.4										
288	134000	8.3	9.4	buried clasts									
289	134000	8.6	9.8	buried clasts				1					
290	134003	9.0	11.1			1							
291	134005	9.0	11.1										
292	134009	9.8	12.2									1	
293	134009	9.9	11.3							1			crab?
294	134012	9.9	11.3	wood							2		
295	134015	10.8	12.4				1	1					
296	134018	10.2	11.7									1	

LEGEND

l	left
r	right
e	edge
ll	lower left
lr	lower right
c	center
u	upper

Frame	Time	Altitude	Width	Comments	Fish	Flatfish	Eelpout	Starish	Anemone	Other	Fish trail	Burrow	Notes
297	134018	9.8	11.4	stick		1						2	
298	134021	8.4	9.6									2	
299	134023	8.4	9.6	numerous small burrows									
300	134027	10.0	11.4		1							2	fish is skate
301	134027	9.8	11.2					1					
302	134030	10.4	13.0										
303	134033	10.4	13.0										? light uc
304	134036	10.8	12.3	broken drum on side									2 ? pale cl
305	134036	13.0	14.8	same drum									scour & lighter sed near drum
306	134039	13.0	14.8									2	? clump urc
307	134042	11.9	13.6			1							
308	134045	11.7	13.4		1	1					1		? c
309	134045	10.4	11.9									1	
310	134048	10.4	11.9										? dark l edge
311	134051	11.8	13.5									1	
312	134056	12.6	14.4								1	1	
313	134054	9.9	11.4									1	
314	134057	9.9	11.4									1	
315	134059	9.9	11.3				1						
316	134059	11.0	11.3									3	
317	134103	10.8	12.1										
318	134106	10.8	12.1								1		
319	134106	10.9	12.5										
320	134108	11.1	12.6										
321	134111	11.1	12.6			1					1		
322	134114	12.0	13.2									1	
323	134114	11.8	13.5										
324	134117	12.3	14.0								1		
325	134120	12.3	14.0										
326	134120	13.6	15.5										
327	134123	11.5	12.9										
328	134126	11.5	12.9										
329	134129	12.5	14.3			2						2	
330	134132	12.1	13.8			1					1		
331	134132	11.1	12.3									1	clump? lr
332	134135	11.8	13.4								1		
333	134138	11.3	12.3										
334	134141	11.3	12.3										
335	134144	10.2	10.9									2	? dark le
336	134147	8.9	10.0				1						? light c
337	134150	8.3	9.2			1						3	
338	134153	8.4	8.9	buried small clasts									
339	134159	8.0	9.0	buried small clasts									
340	134202	7.4	8.6	buried small clasts									
341	134205	7.8	9.0	buried small clasts							1		
342	134208	7.0	8.2	buried small clasts							1		
343	134211	7.7	8.6			1					1	1	
344	134221	9.6	11.1									1	burrow is very large exc
345	134217	8.6	9.9	buried clasts								2	
346	134220	8.2	9.4	buried clasts									

LEGEND	
l	left
r	right
e	edge
ll	lower left
lr	lower right
c	center
u	upper

Frame	Time	Altitude	Width	Comments	Fish	Flatfish	Eelpout	Starish	Anemone	Other	Fish trail	Burrow	Notes
347	134223	9.1	10.4	buried clasts				1					
348	134226	8.7	10.2										
349	134229	8.7	10.1			1					1		
350	134232	10.3	11.8	buried clasts								2	
351	134235	8.6	9.9	buried clasts								1	
352	134241	9.4	10.8									1	
353	134244	9.7	11.4	sticks	1							1	
354	134247	10.2	11.7	sticks								1	
355	134250	9.7	11.0	sticks								1	
356	134253	9.4	10.8	ripples		1	1						
357	134253	9.4	10.8									1	
358	134259	8.8	10.5			1	1						
359	134302	9.2	11.4										
360	134305	9.3	10.6									2	
361	134311	8.6	9.9	ripples									fish mll?, ? two dark circles c
362	134314	8.0	9.6	ripples								1	stick ll, ? dark wiggle lc
363	134317	7.8	9.0	ripples							1		
364	134320	8.0	9.0	buried clasts							1		
365	134323	8.0	9.0	ripples							1	1	
366	134326	9.4	10.8			1						2	
367	134329	8.6	9.9									2	
368	134335	8.4	9.7									3	
369	134337	8.0	9.4										
370	134340	8.6	9.9	ripples								3	
371	134343	7.8	9.0				1				1	3	
372	134346	9.3	10.5	buried clasts						1			lobster? uc
373	134349	8.4	9.7			1					2	3	
374	134352	7.8	9.8			1						3	? med gray c
375	134355	9.7	11.2									3	? pale cl
376	134401	8.1	9.3	buried clasts								2	
377	134404	8.4	9.8									1	
378	134407	8.5	10.0			1						7	
379	134410	8.6	10.0									4	1 burrow quite large
380	134413	8.3	9.6			1						4	
381	134416	8.7	10.0					1				5	
382	134418	8.1	10.0									6	
383	134421	8.1	10.0									8	
384	134423	8.0	9.1									8	
385	134426	8.9	9.0								1	5	
386	134428	7.8	8.8	buried clasts							1		
387	134431	8.1	9.2									2	
388	134434	7.7	8.9										white stick lc
389	134434	8.2	9.4									1	
390	134437	8.6	9.9									3	
391	134440	8.6	9.9					1			2	2	
392	134443	8.6	9.9			1					1	1	
393	134446	8.6	9.9									6	
394	134449	9.0	10.6	buried clasts									? c
395	134449	8.2	9.4										? very dark ur
396	134452	8.7	10.0	some shell hash								3	

LEGEND	
l	left
r	right
e	edge
ll	lower left
lr	lower right
c	center
u	upper

Frame	Time	Altitude	Width	Comments	Fish	Flatfish	Eelpout	Starish	Anemone	OtherFish	trail	Burrow	Notes
397	134455	10.5	12.1			2							
398	134458	9.9	11.4	buried clasts								2	? 2 dark c
399	134501	9.9	11.4					1				3	
Total					`17	52	9	16	7	6	79	217	
Mean		9.3	10.7										
SD		1.6	1.7										

LEGEND

l	left
r	right
e	edge
ll	lower left
lr	lower right
c	center
u	upper

Appendix B
Coverage Rates and Cost Estimates

SYSTEM	RATE	SWATH	SWATH	SPEED	SPEED	AREA PER DAY		COST PER AREA	
	$/day	meter	nautical mile	knots	kilometer/hour	nautical mile^2/day	kilo-meter^2/day	$/nautical mile^2	$/kilometer^2
LLSS	$4,850	10	0.0054	3.00	5.56	0.292	1.002	$16,582	$4,842
SIDE-SCAN	$2,850	50	0.02699	4.00	7.41	1.948	6.676	$1,463	$427
VIDEO	$2,950	1	0.00054	0.54	1.00	0.005	0.018	$552,640	$162,385
FILM	$3,250	1	0.00054	0.54	1.00	0.005	0.018	$608,841	$178,899

COST ASSUMPTIONS	
100' BOAT	$2,500
50' BOAT	$1,300
TECHNICIAN	$300
SR. TECHNICIAN	$600
LLSS	$900
SIDESCAN	$400
VIDEO	$500
FILM	$500
NAVIGATION	$250

- Time per Lane (1 Nautical Mile Lanes)
  Including Ten Minute Turns =
  Lane Length/Speed +0.166 hr = hr/Lane
- Lanes Per Day=
  18 hr/ (hr/Lane)
- Area Per Day=
  Lanes Per Day X Swath Width X Lane Length

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13. ABSTRACT *(Maximum 200 words)*

This paper is an elaboration of an earlier review of sensors that are used for efficient assessment of submerged coastal habitats and biological resources (Rhoads et al. 1994). This document outlines in greater detail the operational principles of the laser line scan system (LLSS), method of deployment, data acquisition, and post-cruise data analysis protocols. While the LLSS system has a wide range of potential applications, the emphasis here is on mapping and monitoring seafloor (or lake bottom) features that are of particular interest to the U.S. Army Corps of Engineers such as mapping of sediment types, biological resources, dredged material footprints, and underwater structures such as submerged parts of dikes, dams, levees, or discarded waste containers.

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